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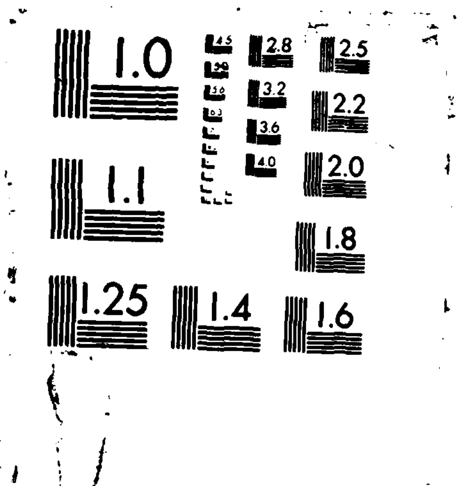

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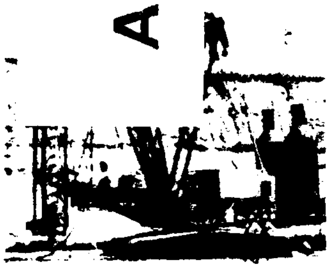

GEOTECHNICAL LABORATORY

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DEVELOPMENT OF A LABORATORY TECHNIQUE FOR CORRECTING RESULTS OF UNDRAINED TRIAXIAL SHEAR TESTS ON SOILS CONTAINING COARSE PARTICLES FOR EFFECTS OF MEMBRANE COMPLIANCE

by

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Undrained loading tests are widely used to assess the susceptibility of soils to liquefaction. Variation, with changes in effective confining stress, of the penetration of the membrane confining a soil sample into the voids between the particles (membrane compliance) invalidates the assumed testing conditions of constant volume without drainage. This can have a serious detrimental impact on the accuracy and validity of such tests, particularly for medium to coarse sands as well as gravels, and no completely reliable procedures currently exist either for mitigation of membrane compliance effects during testing or for post-test correction of the results of conventional undrained tests. The objective of this research program has therefore been to develop and implement improved laboratory testing procedures for elimination of membrane compliance effects during undrained triaxial testing. Mitigation of compliance effects during testing was accomplished by first predetermining the magnitude of volumetric compliance as a function of effective confining

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stress and soil parameters, and then using computer-controlled injection or removal of water to continuously eliminate (offset) membrane compliance effects during all stages of "undrained" cyclic or monotonic loading tests. Small-scale (2.8-in. diameter) undrained monotonic and cyclic triaxial tests were performed on samples of a uniformly-graded medium sand. Both types of tests were performed, with and without implementation of the computer-controlled membrane compliance mitigation process developed, on identically prepared samples. The results of this testing program support the validity and usefulness of this approach and suggest that computer-controlled injection/removal represents the first fully successful method for elimination of membrane compliance effects in undrained testing. The procedures developed in these studies are suitable for adaptation to large-scale triaxial testing of gravelly soils.

PREFACE

This report was prepared under contract as part of the project authorized by the Office, Chief of Engineers, under "Civil Works Investigation Studies (CWIS)," Materials Research Area, Soils Research Program, Work Unit 32342, "Testing Large-Particled Soils."

The work was conducted and reported by Professor Raymond B. Seed and Hossain Anwar of the Leland Stanford Junior University, Palo Alto, California. The Contracting Officer's Representative and Principal Investigator for CWIS 32342 was Dr. Victor H. Torrey III, US Army Engineer Waterways Experiment Station (WES), Geotechnical Laboratory (GL), Soil Mechanics Division (SMD).

The Contracting Office was the US Army Research Office, Research Triangle Park, North Carolina, which let the work for the period of 2 May to 30 October 1986 under Scientific Services Program Contract No. DAAG 29-81-D-0100, Delivery Order No. 2263. Funding was provided by WES.

Conduct of CWIS 32342 is under the general direction of Dr. William F. Marcuson III, Chief, GL; and Mr. Clifford L. McAnear, Chief, SMD, GL.

COL Allen F. Grum, USA, was Director of WES during the preparation of the report. COL Dwayne G. Lee, CE, is the present Commander and Director. Dr. Robert W. Whalin is Technical Director.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 INTRODUCTION

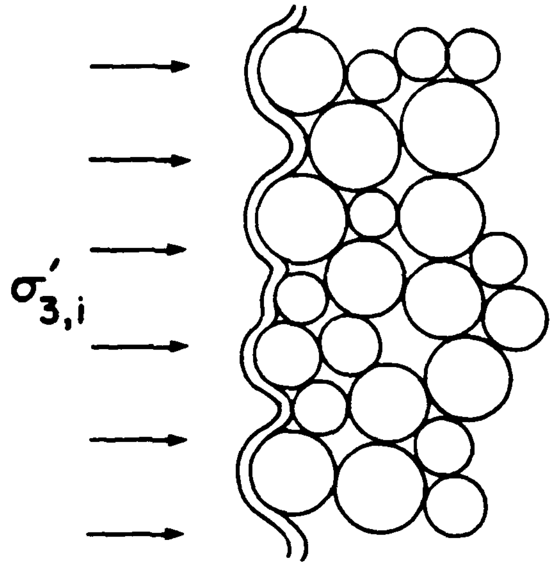
1.1 Problem Definition:

Undrained loading tests are widely used to assess the susceptibility of saturated soils to liquefaction as a result of earthquakes, blast-induced loading, pile driving, etc. In such tests, saturated soil samples are subjected to cyclic or monotonic loading under undrained conditions in order to simulate field loading conditions. Such applications of stress to relatively loose soils cause a progressive increase in pore pressure within the sample, progressively reducing the effective confining stresses and weakening the sample, until strain amplitudes become large indicating the onset of liquefaction or cyclic mobility. In field situations liquefaction, or loss of strength due to pore pressure increases, may result in sudden and catastrophic soil failure.

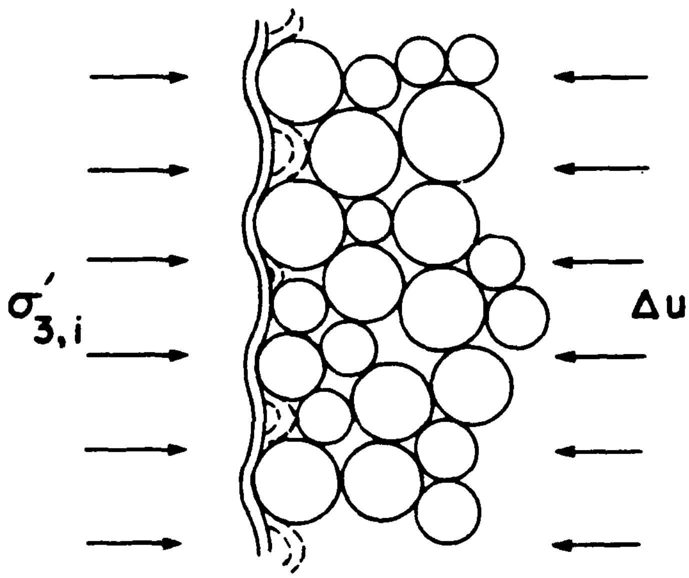
Several types of tests (e.g., triaxial, simple shear, and torsional shear tests) are used to assess soil susceptibility to liquefaction. Implicit in the performance of all of these tests is the assumption that no sample volume changes occur during the test except for a nominal compression of pore water as a result of increased pore pressure. As first observed by Newland and Allely (1959), however, penetration of the rubber membranes used to confine the samples into the surficial voids of test specimens of coarse-grained soils varies as a function of the applied or effective confining pressure. Thus, as the effective confining pressure decreases as a result of sample pore pressure increases, the corresponding reduction in membrane penetration results in changes in sample volume (membrane compliance) during "undrained" testing. This can lead to a serious overestimation of the resistance of the sample to liquefaction.

Figure 1-1 illustrates the penetration of a confining membrane into the surficial or peripheral voids of a soil sample under an initial effective confining stress of $\sigma_{3,i}'$, as well as the effects of an increase in internal sample pore pressure (Δu) resulting in a decrease in effective confining stress (σ_3'). This in turn results in a decrease in membrane penetration into the peripheral voids, creating additional space (sample volume) into which sample pore water may migrate. This reduction in membrane penetration and accompanying volume increase causes pore pressure increases to be less than those which would occur in truly undrained tests performed at constant volume, thereby increasing the apparent strength of the soil and leading to an unconservative assessment of liquefaction susceptibility.

The degree to which membrane penetration may affect the results of liquefaction tests is a function of the soil grain size and the overall dimensions of the test sample. Thus, with fine sands and silts, membrane compliance effects may be negligible since even thin membranes cannot penetrate significantly into the small surficial voids (Martin et al., 1978; Ramana and Raju, 1982). For such soils at low relative densities, liquefaction can readily be observed to occur in laboratory tests, as illustrated by the data in Figure 1-2 for Sacramento River fine sand with an initial relative density of 35% subjected to undrained monotonic loading. For coarse sands, however, membrane compliance effects can have a significant influence on test results, as illustrated by the data in Figure 1-2 for a coarse, uniformly graded sand with the same initial relative density subjected to the same loading conditions. This coarser sand, in spite of the low relative density, shows no reduction in strength with increasing strain or other evidence of liquefaction, although it would be expected to do so under truly undrained conditions in the field. This may be due in large measure to the significant effects of membrane compliance on the test results.



a) Initial Conditions



b) Conditions After Pore Pressure Increase

Figure 1-1: SCHEMATIC REPRESENTATION OF MEMBRANE PENETRATION

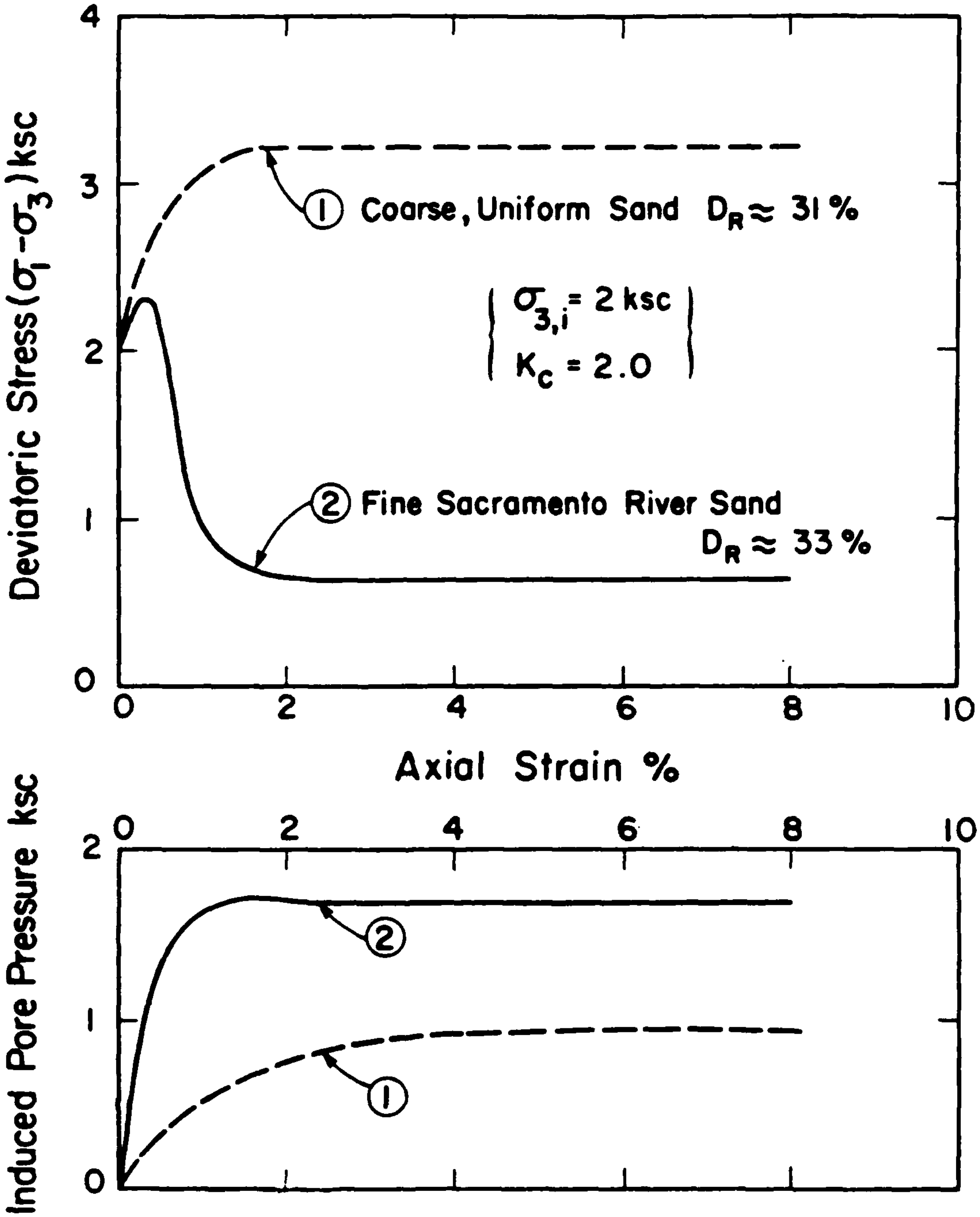


Figure 1-2: <u>TYPICAL AC-U TRIAXIAL TEST RESULTS FOR COARSE AND FINE SANDS AT LOW INITIAL RELATIVE DENSITIES</u>

Membrane compliance can have a serious deleterious influence on the results of conventional "small-scale" (< 3-inch diameter) undrained triaxial tests of medium and coarse sands. Coarse sands can be successfully tested, at significant cost, in the few large-scale (> 12-inch diameter) triaxial testing facilities currently in existence, but even these few large-scale facilities are not able to perform representative undrained tests on coarser, gravelly soils. In fact, it is virtually impossible to demonstrate the occurrence of liquefaction in laboratory tests on even very loose coarse gravelly soils because of membrane compliance effects--though field evidence indicates that this is not necessarily representative of the in-situ behavior of these soils, as coarse soils such as gravels have been observed to liquefy in the field under earthquake loading (e.g., Ishihara, 1984; Coulter and Migliaccio, 1966; Chang, 1978; Youd et al., 1984; and Harder, 1984).

In spite of these evidences that liquefaction can occur in coarse-grained soils such as gravels in the field, currently available laboratory tests have been unable to accurately reproduce this behavior when applied to coarse soils due to the magnitude of the effects of membrane compliance on the test results. Thus it is of paramount importance to develop testing techniques for coarse-grained soils which will, as completely as possible, eliminate the effects of membrane compliance on the test results. Such a development may be expected to open the doors to better evaluations of the liquefaction behavior of medium to coarse sands and gravels than has been possible in the past.

This is not meant to suggest that important progress in the investigation the effects of membrane compliance has not already been made (see Chapter 2). However, while methods have been developed for partially reducing the influence of membrane compliance effects, no procedure has been developed for eliminating these effects completely. Nor are completely reliable procedures

yet available for post-test correction of conventional results in order to compensate for membrane compliance effects. Moreover, in the absence of any method for fully eliminating the effects of membrane compliance during testing, no reliable data exists upon which to base verification of such post-test correction methods. Accordingly, there is a need to develop improved testing procedures and equipment in order to effectively eliminate the adverse effects of membrane compliance and/or to develop and demonstrate the adequacy of appropriate methods of interpreting the results of conventional tests in order to obtain a valid characterization of the undrained loading response properties of coarse-grained soils.

1.2 Scope of Research Performed:

The purpose of this research investigation was to (a) develop techniques to isolate and characterize the effects of membrane compliance during undrained triaxial testing of saturated soils, (b) develop and implement a technique to eliminate the adverse influence of membrane compliance during undrained testing (develop a technique for full and continuous mitigation of membrane compliance effects during undrained testing), and (c) experimentally demonstrate the effectiveness of the membrane compliance mitigation methodology developed.

The membrane compliance mitigation procedures developed consisted of first pre-determining the volumetric magnitude of membrane compliance for a given soil as a function of sample stress state, and then using a computer-controlled process to continuously inject or remove water from the sample during testing in order to exactly offset the volumetric error induced by membrane compliance. In order to implement this technique, it was necessary to demonstrate that volumetric compliance could be reliably measured prior to testing, and that it could be reliably characterized in such a manner that the

computer-controlled injection/removal process could be based on monitoring of changes in sample effective confining stress and geometry. In addition, injection/removal had to be a continuous process and one which would not introduce new errors in the test results.

All of these objectives were achieved. Methods were developed for characterization of the magnitude of volumetric membrane compliance, and factors affecting compliance magnitude were investigated. It was demonstrated that the volumetric error induced as a result of membrane compliance was a direct and repeatable function of changes in effective sample confining stress, and that monitoring these changes in effective stress provided a suitable basis for continuous computer-controlled injection/correction during "undrained" testing. Undrained monotonic and cyclic triaxial loading tests were performed on samples of a uniformly graded medium sand, with and without implementation of the computer-controlled membrane compliance mitigation methodology developed, in order to provide a basis for evaluating the effectivness of the compliance mitigation procedures. The results of these tests support the effectiveness of the membrane compliance mitigation procedures proposed and implemented in these studies.

All testing performed in the course of these studies used conventional "small-scale" triaxial testing apparatus capable of testing 1.4- and 2.8-inch diameter samples. An overriding consideration throughout the course of this investigation, however, was the requirement that the procedures developed be suitable for adaptation to large-scale triaxial testing of coarse, gravelly soils in specimens of greater than 12-inch diameter.

Chapter 2 presents a review of previous research regarding (a) measurement and characterization of membrane compliance and (b) mitigation of membrane compliance effects in undrained testing. Chapter 3 describes the

computer-controlled injection/correction process developed to mitigate compliance effects during testing, and also presents an overview of studies performed to develop and verify methods for pre-testing characterization of membrane compliance. Chapter 4 presents the results of undrained monotonic and cyclic triaxial tests of a uniformly graded medium sand with and without implementation of the computer-controlled membrane compliance mitigation methods developed, and examines the effectiveness of these mitigation methods based on examination of these test results. Chapter 5 summarizes these studies, and presents conclusions as well as recommendations for adaptation of the membrane compliance mitigation procedures developed to large-scale undrained triaxial testing of coarse gravelly soils.

2.0 SUMMARY OF PREVIOUS WORK

Newland and Allely (1959) were the first to draw attention to the problems arising as a result of membrane penetration. Since their early work, a number of investigators have worked on the development of procedures for evaluation and/or mitigation of compliance effects in undrained testing. In spite of progress made, however, it appears that: (a) no reliable procedures exist for correction of conventional test results in order to compensate for compliance effects; (b) as a result of an absolute upper limit on sample size imposed by available large-scale test apparatus, compliance effects preclude representative undrained testing of saturated soils coarser than coarse sands to fine gravels; and (c) the true undrained strength and liquefaction characteristics of soils coarser than fine sands cannot be determined using most conventional (not large-scale) testing apparatus.

2.1 Evaluation of Membrane Compliance Effects:

Considerable progress has been made during the past 25 years in the development of methods for evaluating the volumetric magnitude of membrane compliance effects, a necessary first step in the development of procedures for mitigation of compliance effects. A common feature of all of the methods developed to date for evaluation of membrane compliance effects is the use of fully drained tests to determine the volumetric magnitude of membrane penetration changes as a result of changes in effective sample confining stress. When the effective stress applied to a saturated soil sample confined by a membrane is caused to change under drained conditions, the result is a change in sample volume which is conventionally evaluated by measuring the volume of water (ΔV) either expelled or drawn into the sample. This water volume is, however, actually the sum of two volume change components. One component is

the "true" or skeletal volume change of the soil sample, which is equal to the "true" sample volumetric strain ($\varepsilon_{v,s}$) multiplied by the sample volume (V_s). The second component of apparent volume change measured is due to variation in membrane penetration (membrane compliance), and this can be expressed as the compliance-induced volume change per unit area of the membrane (δV_m) multiplied by the total membrane area (A_m). These quantities are related by the simple equation

$$\Delta V = [\varepsilon_{v,s} \cdot V_s] + [\delta V_m \cdot A_m] \tag{2-1}$$

The development of methods for evaluation of volumetric membrane compliance involves development of techniques for differentiating between these two volume change components ($\varepsilon_{v,s}$ and δV_m). This is not difficult when dealing with large-scale triaxial samples (diameters $\geq$ 12 inches) as both the axial and radial sample strains can be measured directly in order to evaluate the "true" sample skeletal volume change. Radial strains for such large-scale samples are measured using "girth belts" which measure sample circumference during application of confining stress changes, as illustrated schematically in Figure 2-1. When dealing with smaller-scale samples (diameters $\leq$ 6 inches), however, it is exceedingly difficult to measure radial strain with sufficient accuracy by this method, and other techniques must be employed to differentiate between the volume change components due to sample skeletal volume change and membrane compliance.

2.1.1 Methods for Membrane Compliance Measurement:

Newland and Allely (1959) assumed isotropic compression and rebound of triaxial specimens under varying isotropic effective confining stresses, and calculated volumetric membrane compliance as the difference between the total volumetric strain (ε_v) measured in drained tests on saturated specimens and

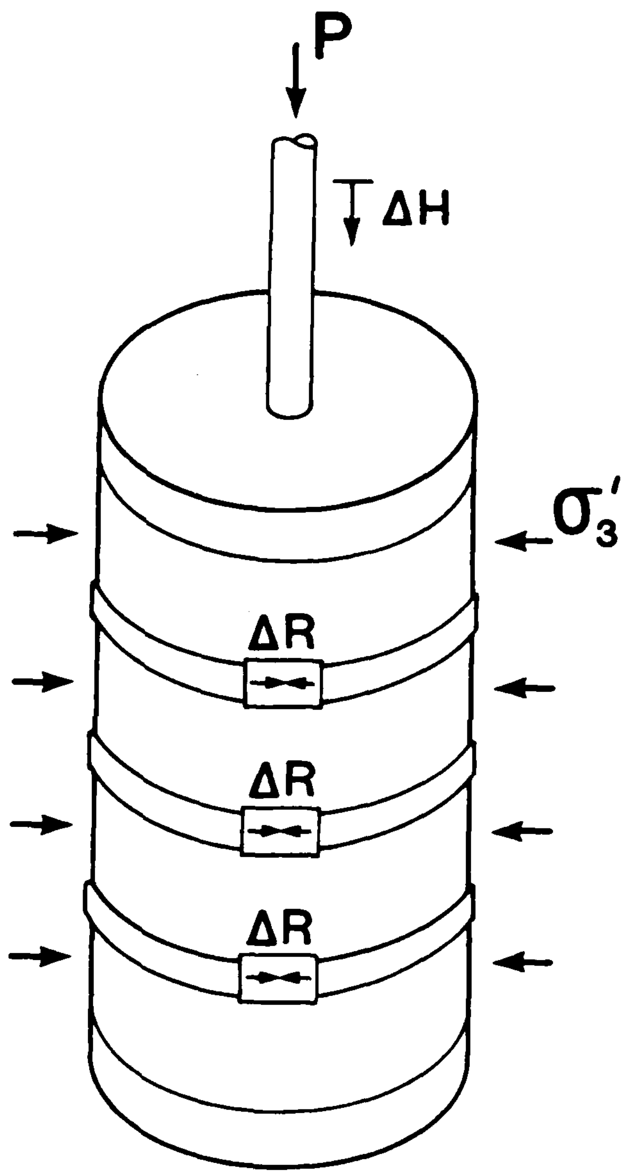


Figure 2-1: SCHEMATIC ILLUSTRATION OF THE USE OF GIRTH BELTS TO MEASURE RADIAL STRAINS

three times the relatively easily measured axial strain ($3 \times \varepsilon_A$) which was assumed to be equal to the "true" skeletal volume change of the sample.

Roscoe et al. (1963) noted that the assumption of isotropic behavior was unrealistic for cohesionless soils, and developed an alternative method using 1.5-inch diameter triaxial specimens containing central brass rods. The height of the rod was the same as that of the specimen, and samples were tested with rod diameters of 0.25 and 1.37 inches. An additional sample with no rod (rod diameter = zero) was also tested. Volumetric membrane compliance was then estimated by plotting measured volume changes (for a given change in confining stress) versus rod diameter and using a straight line extrapolation to estimate the volume change for a sample with a rod diameter equal to the sample diameter, at which point all remaining measured volume changes were assumed to be due to membrane penetration effects. El-Sohby (1964) and Lee (1966) also used the central rod method, with minor variations in rod sizes, to evaluate compliance effects, as illustrated schematically in Figure 2-2(a).

Thurairaja and Roscoe (1965) performed a subsequent study and concluded that the central rod method suffered from a number of drawbacks and in fact was not markedly better than Newland and Allely's original method based on assumed sample isotropy. Steinbach (1967) concurred, and used the original Newland and Allely method in a parametric study of compliance effects. Raju and Sadasivan (1974) suggested that the main drawbacks with the central rod method were twofold: (a) the rod itself caused stress concentrations within the sample; and (b) the assumption of a linear relationship between rod diameter and volumetric compliance was incorrect. They developed a modified top platten which had a central hole and could thus slide down over the central rod in order to provide a somewhat improved stress field within the sample, and suggested that a linear relationship should exist between volumetric compliance and actual sample volume, not rod diameter, as illustrated

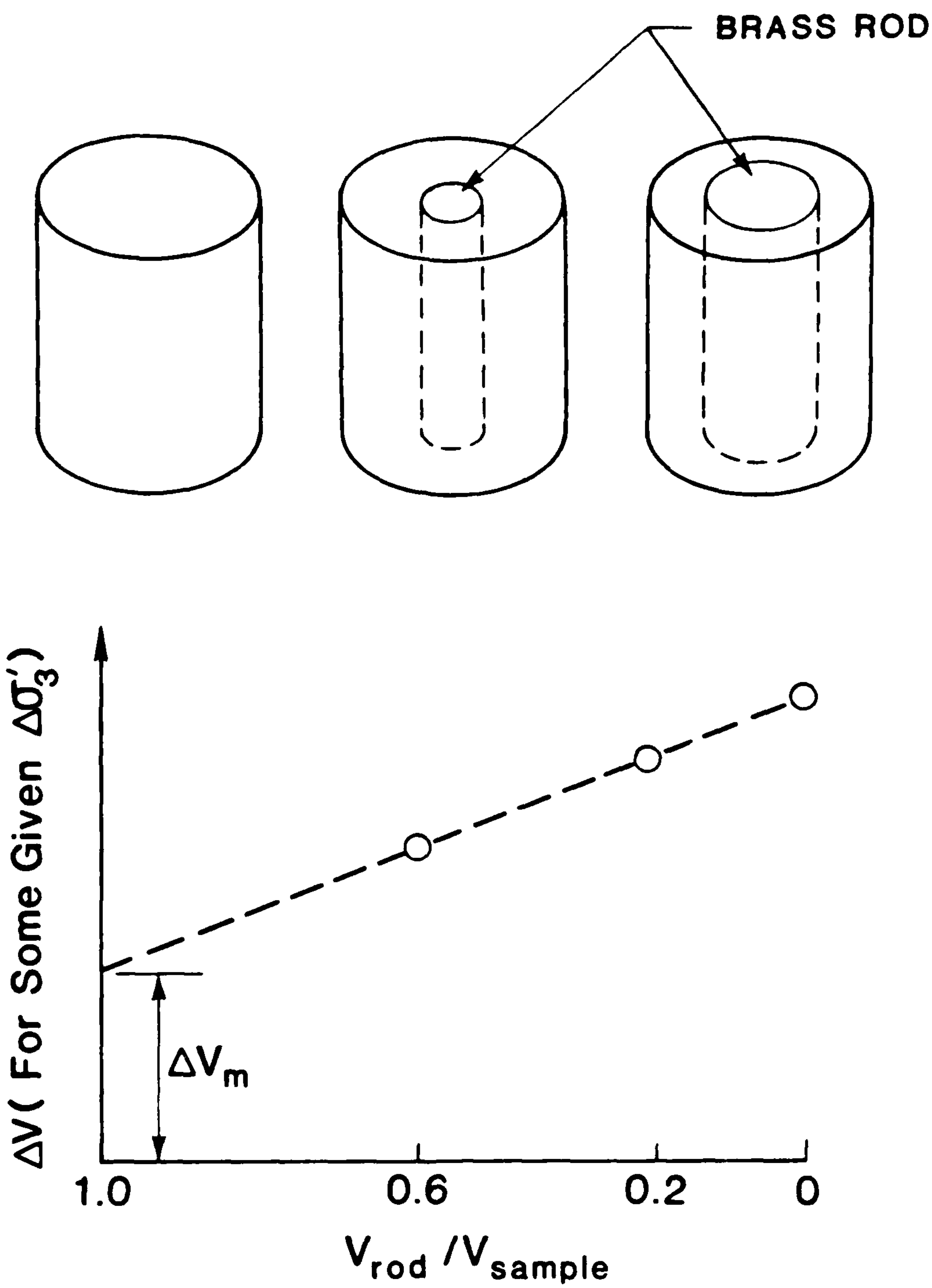


Figure 2-2: USE OF CENTRAL RODS IN TRIAXIAL SAMPLES TO EVALUATE MEMBRANE COMPLIANCE

schematically in Figure 2-2(b). This improved the central rod method, but the method still has a number of significant drawbacks including the following:

(1) Even with the improved top platen, friction between the rigid inclusion represented by the central rod and the soil sample results in stress concentrations and stress fields which vary as a function of the rod and sample diameters, so that samples with rods of different diameter experience different "true" skeletal volumetric strains, and

(2) It is difficult to fabricate samples of identical density and soil "fabric" while working around the interference of rods of different diameters.

Frydman et al. (1973) developed a method for evaluating volumetric compliance using hollow cylindrical samples. Instead of a central brass rod, the samples were constructed with central cylindrical holes of various diameters (hollow cylindrical samples) and the confining pressure within the central holes was varied in conjunction with the pressure on the outer wall of the sample. For a given variation in effective confining stress, the volumetric strain (ε_v) was plotted versus the ratio between membrane surface area and sample volume (A_m/V) for different internal hole diameters. The points were found to plot on a straight line which intercepted the ε_v axis (at $A_m = 0$) at the true sample $\varepsilon_{v,s}$, and which had a slope equal to the unit volumetric membrane penetration (volumetric membrane compliance per unit membrane area; δv_m). This hollow cylinder method provides samples with more nearly similar (though not identical) stress fields than does the central rod method, but still suffers from the considerable difficulty associated with fabrication of samples of identical density and soil fabric.

Kiekbusch and Schuppener (1977) developed a procedure in which a saturated soil sample was placed in a shallow well in the base of a triaxial cell, with

the top surface of the sample flush with the base of the cell, and covered with a sheet membrane. Pressure was applied to the top of the membrane, and a sensitive deflection guage measured the vertical deflections of a tripod mounted on the membrane at the top of the sample, allowing differentiation between volume changes due to membrane penetration and those due to sample compression. The principal drawback to this approach is the difficulty in measuring, with adequate accuracy, the extremely small deflections of the tripod mount used to measure "true" sample skeletal volumetric changes.

Vaid and Negussey (1984) examined the fundamental assumptions involved in the assessment of sample volume changes due to membrane compliance in triaxial tests on granular soils by methods that use dummy rod inclusions or assume isotropic behavior of sand during loading, and concluded that the necessary assumptions make these methods invalid. They suggested instead that reliable determinations can be made either by performing multiple isotropic loading tests on specimens having different diameters and then solving for the component of volume change due to membrane compliance effects (a method previously employed by Wong, 1983), or by performing single tests on a triaxial specimen subjected to isotropic unloading, in which case the assumption that volumetric sample strain is equal to three times the axial strain is nearly valid. They performed tests of both types on samples of Ottawa sand, a uniformly graded medium sand at a relative density of approximately $D_R = 50\%$, and found that both methods yielded similar results.

In considering Vaid and Negussey's proposed assumption of isotropic strain behavior during unloading (rebound), it should be noted that for the Ottawa sand tested by Vaid and Negussey the volume change due to membrane compliance was greater than that due to sample skeletal volume changes, so that errors introduced as a result of assuming isotropic rebound behavior were

not as significant for this material as they would be for finer-grained soils. A more refined examination of this isotropic rebound assumption, undertaken as part of these research studies (see Section 3.2), showed that sample strains in rebound are indeed more nearly isotropic than in initial compression, but that they are not fully isotropic. Moreover, the relationship between axial strain and radial strain ($\varepsilon_a/\varepsilon_r$) in rebound was found to be a function of sample density. Assumption of isotropic rebound behavior can introduce significant error in the measurement of membrane compliance for soils (and sample sizes) in which the volume changes due to membrane penetration variation are not large relative to sample skeletal volume changes resulting from variation of effective sample confining stress.

2.1.2 Recommended Small-Scale Membrane Compliance Measurement Method:

It is hereby suggested that the best method of evaluating membrane compliance in conventional (small-scale) triaxial testing involves performing fully-drained isotropic loading and unloading tests on two samples of the same material, prepared by identical procedures and to the same density but with different sample diameters, and then solving for the component of volume change due to membrane compliance. This involves the assumption that sample skeletal volumetric strains in both samples will be identical under identical loading conditions. In order to achieve this, the two samples must have the same height-to-diameter ratio, must be prepared by identical procedures and to the same density, must have the same end conditions (e.g., rough or lubricated), and must be subjected to the same (isotropic) stress conditions so that the samples represent ideal scale models of each other. Similarity of volumetric strain behavior of the samples under isotropic loading will then be assumed, in view of the geometric similarity. It is suggested, therefore, that both samples should have <u>identical</u> height/diameter ratios and end

conditions (e.g., rough or lubricated) in order that both samples represent ideal scale models of each other. These rigorous constraints regarding sample modelling similarity had not been previously proposed, but are considered vital in order to provide for ideal similarity of "true" sample volumetric strains. In adddition, the method should only be considered valid so long as a minimum ratio of sample diameter:maximum particle size greater than or equal to 12:1 is maintained in order to preclude localized stress concentrations due to adverse scale effects near large particles.

If these conditions are met, then under identical drained isotropic loading or unloading of both samples, the total volume change (ΔV) measured at any given confining stress change can be expressed for each sample as

$$\Delta V_1 = \left(\varepsilon_{v,s} \cdot V_{s,1}\right) + \left(\delta V_m \cdot A_{m,1}\right) \qquad (2\text{-}2a)$$

$$\Delta V_2 = \left(\varepsilon_{v,s} \cdot V_{s,2}\right) + \left(\delta V_m \cdot A_{m,2}\right) \qquad (2\text{-}2b)$$

where $\Delta V_1, \Delta V_2$ = the measured volume changes of samples 1 and 2 at some given sample confining stress,

$\varepsilon_{v,s}$ = the sample skeletal volumetric strain,

$V_{s,1}, V_{s,2}$ = the volumes of samples 1 and 2,

δV_m = membrane compliance-induced volume change per unit area of membrane, and

$A_{m,1}, A_{m,2}$ = the membrane/sample contact areas of samples 1 and 2.

As the only two unknowns in Equations 2-2(a) and (b) are $\varepsilon_{v,s}$ and δV_m, these equations can be rearranged and δV_m can be found directly as

$$\delta V_m = \frac{\left(V_{s,2} \cdot \Delta V_1\right) - \left(V_{s,1} \cdot \Delta V_2\right)}{\left(V_{s,2} \cdot A_{m,1}\right) - \left(V_{s,1} \cdot A_{m,2}\right)} \qquad (2\text{-}3)$$

This procedure appears to overcome the shortcomings of existing methods for compliance evaluation, and as long as the two samples have the same height to diameter ratio and end conditions, involves no idealized assumptions

regarding sample strain behavior and no linear extrapolation of measurements. In addition, this two-sample "scale model" method has the following advantages:

1. Sample preparation procedures may be the same as will be subsequently used for actual undrained testing, and

2. The method requires no extensive modification of existing conventional triaxial test apparatus, and may thus be widely implemented.

This two-sample "scale model" method was the basis for all evaluation of membrane compliance performed as part of these studies.

2.1.3 Summary of Membrane Compliance Measurement Research:

Ramana and Raju (1982) summarized the findings of previous studies of membrane compliance, and proposed an empirical equation for estimation of unit volumetric membrane penetration (δv_m) as a function of: (a) grain size (D_{50}), (b) effective confining pressure, and (c) sample density. This empirical relationship is applicable only to uniformly graded soils. Ramana and Raju found that δV_m was strongly influenced by grain size and effective confining stress, and only moderately influenced by sample density.

A more complete investigation of factors affecting volumetric membrane compliance was performed as part of these studies, and a brief summary of the results is presented in Section 3.2 of this report. Sample grain size D_{20} was found to correlate significantly better than D_{50} with δV_m, and sample gradation or grain size distribution was found to also exert a strong influence on membrane compliance behavior. Unit membrane compliance was found to be an essentially linear function of the $\log_{10}$ of effective confining stress over the effective confining stress ranges of primary interest in triaxial testing (2 psi $\leq \sigma_3' \leq$ 60 psi). A number of additional factors were investigated and found to have little or no significant effect on membrane compliance. These

factors included: (a) sample density, (b) sample particle angularity, (c) sample fabric or method of sample preparation, and (d) membrane thickness or stiffness. In addition, it was found that samples cyclically loaded to full liquefaction (r_u = 100%) and then allowed to re-consolidate exhibited membrane compliance behavior essentially identical to that of samples not loaded prior to measurement of membrane compliance.

2.2 Mitigation of Membrane Compliance Effects:

The studies described in Sections 2.1 and 3.2 provide a logical starting point for the development of procedures for mitigation of membrane compliance effects as described below. Methods for mitigation of, or compensation for, membrane compliance effects fall into three categories:

1. Use of larger sample sizes in order to reduce the proportional impact of compliance effects,
2. Post-testing correction of test results in order to compensate for compliance effects, and
3. Mitigation of compliance effects during testing.

2.2.1 Use of Large Sample Sizes:

Membrane compliance effects are more pronounced in coarser soils, where the membrane can penetrate deep into the large peripheral surface sample voids. The use of larger samples which have a larger ratio of total volume to peripheral surface area, reduces the impact of volumetric compliance on the induced pore pressures (Martin et al., 1978). This is because, as illustrated in Figure 2-3, sample volume increases with the third power of sample diameter, but sample membrane surface area increases only with the square of sample diameter. Membrane compliance effects are thus greatly reduced when sample size is large relative to grain size. Typical triaxial tests using samples two to three inches in diameter provide good results, with minimal influence

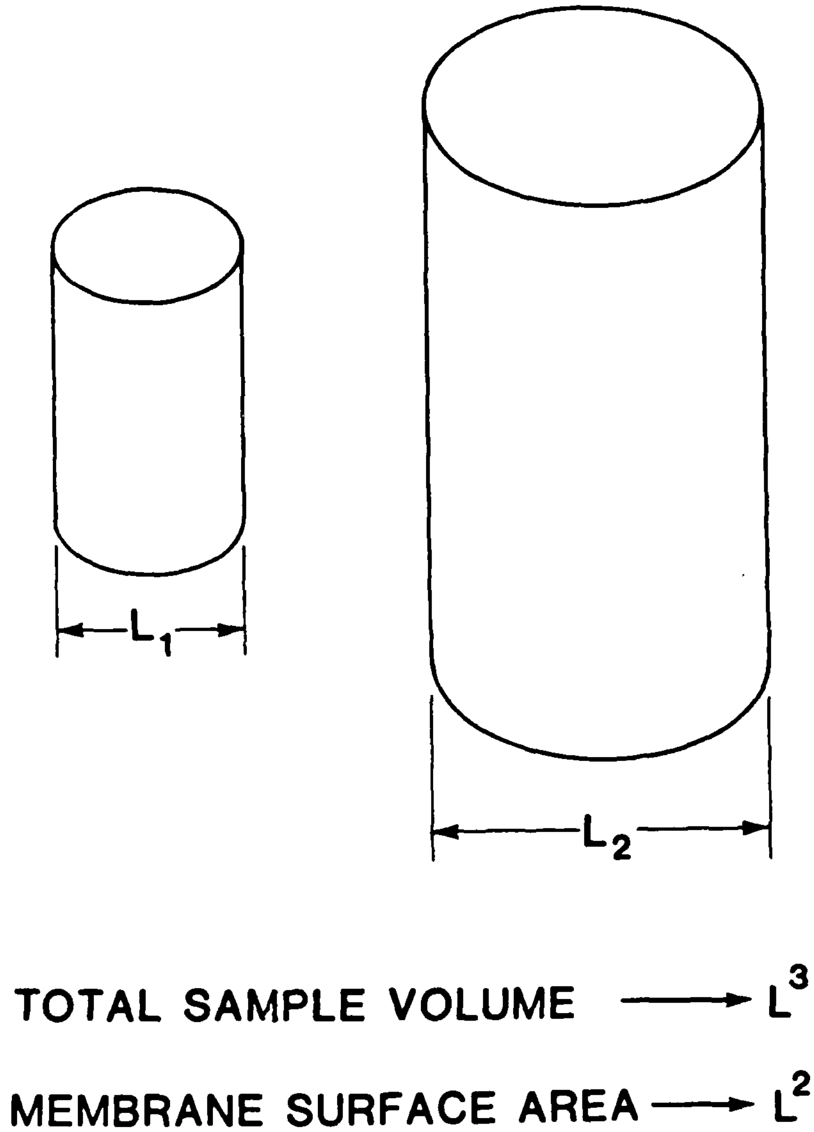


Figure 2-3: SCALE EFFECTS: INFLUENCE OF SAMPLE SIZE ON THE RATIO OF SAMPLE VOLUME TO MEMBRANE SURFACE AREA

of membrane compliance effects, for silts and fine sands. In most conventinal triaxial test apparatus, however, as well as simple shear and torsional shear apparatus, compliance effects are significant for medium and coarse sands. As a result of this, most conventional testing apparatus cannot be used to perform truly representative undrained tests on soils coarser than fine sands. A few very large-scale triaxial test facilities exist in which samples up to approximately one meter in diameter may be tested, allowing testing of somewhat coarser soils. Such large-scale tests are too expensive for most applications, however, and even these very few large-scale facilities do not adequately reduce the effects of membrane compliance for representative testing of soils coarser than fine gravels.

2.2.2 Post-Testing Correction of Test Results:

A number of "theoretical" procedures have been developed for post-testing "correction" of the results of conventional tests in order to compensate for membrane compliance effects, including the examples which follow. Martin, et al. (1978) developed a theoretical procedure for the correction of test results subsequent to completion of cyclic testing based on a fundamental model for pore pressure generation (Martin et al., 1975), which involved a number of empirical parameters determined by soil testing. Baldi and Nova (1984) proposed a similar theoretical post-testing correction procedure applicable only to single-cycle tests based on estimation of sample compressibility as a function of sample stress state. Raju and Venkatamura (1980) proposed a third theoretical post-testing correction procedure based on a simplified version of the theoretical model for compliance effects on pore pressure during undrained testing developed by Lade and Hernandez (1977).

Martin et al. noted that although these types of correction procedures provide a qualitative basis for estimating the nature of "corrected" sample

behavior, the proposed corrections are only theoretical and do not represent a reliable means of quantitatively compensating for compliance. In order to represent a viable method of correction for membrane compliance effects, such corrections must either be based on empirical correlations between conventional tests and tests in which compliance effects have been mitigated, or must be verified by means of such comparative tests. This is because the nature of compliance effects is such that pore pressure generation is affected, in turn affecting the effective confining stresses, which then affect sample strength and stress-strain behavior, and this again affects subsequent pore pressure generation, etc., as illustrated schematically in Figure 2-4. This mutual inter-relationship between confining stress, strength, stress-strain and pore pressure generation cannot yet be modelled with sufficient accuracy to provide a reliable basis for quantitative correction of test results for compliance effects. Moreover, in the absence of comparative test data from tests in which membrane compliance effects are and are not successfully mitigated, it is not possible to properly evaluate the accuracy and reliability of theoretical post-testing correction methods.

2.2.3 Mitigation of Compliance Effects During Testing:

A number of approaches have been employed in attempting to reduce or eliminate the effects of membrane compliance during undrained testing of saturated soils. Basic approaches attempted to date can be divided into six broad categories, as listed in Table 2-1. A brief discussion of each of these methods follows.

(1) Use of protective plates between the rubber membrane and sample grains:

Lade and Hernandez (1977) mounted brass plates inside the membrane around triaxial samples as shown in Figure 2-5(a) in order to eliminate compliance

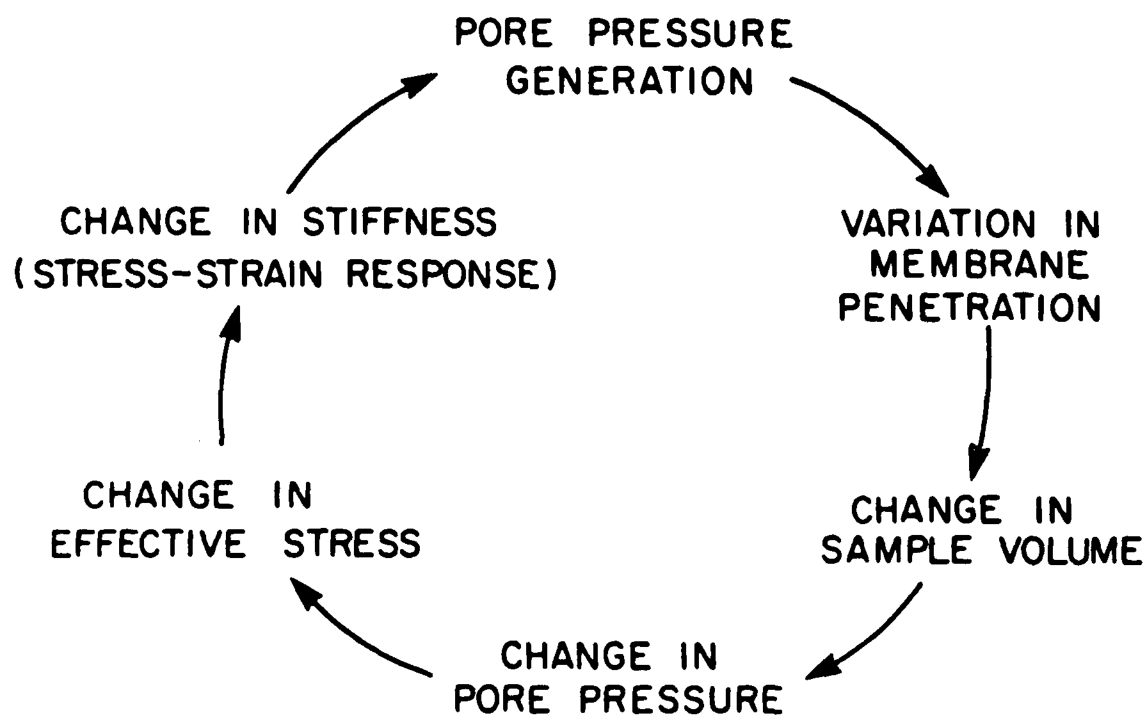


Figure 2-4. THE MUTUAL INTERRELATIONSHIP BETWEEN SAMPLE STRESS, STRAIN, AND MEMBRANE COMPLIANCE

Table 2-1: Method for Mitigation of Membrane Compliance Effects During Undrained Testing

1. Use of protective plates between the rubber membrane used to confine a soil sample and the sample soil grains.

2. Infilling of external peripheral voids in the membrane face at the condition of maximum membrane penetration prior to testing.

3. Filling of internal sample voids directly adjacent to the membrane prior to testing.

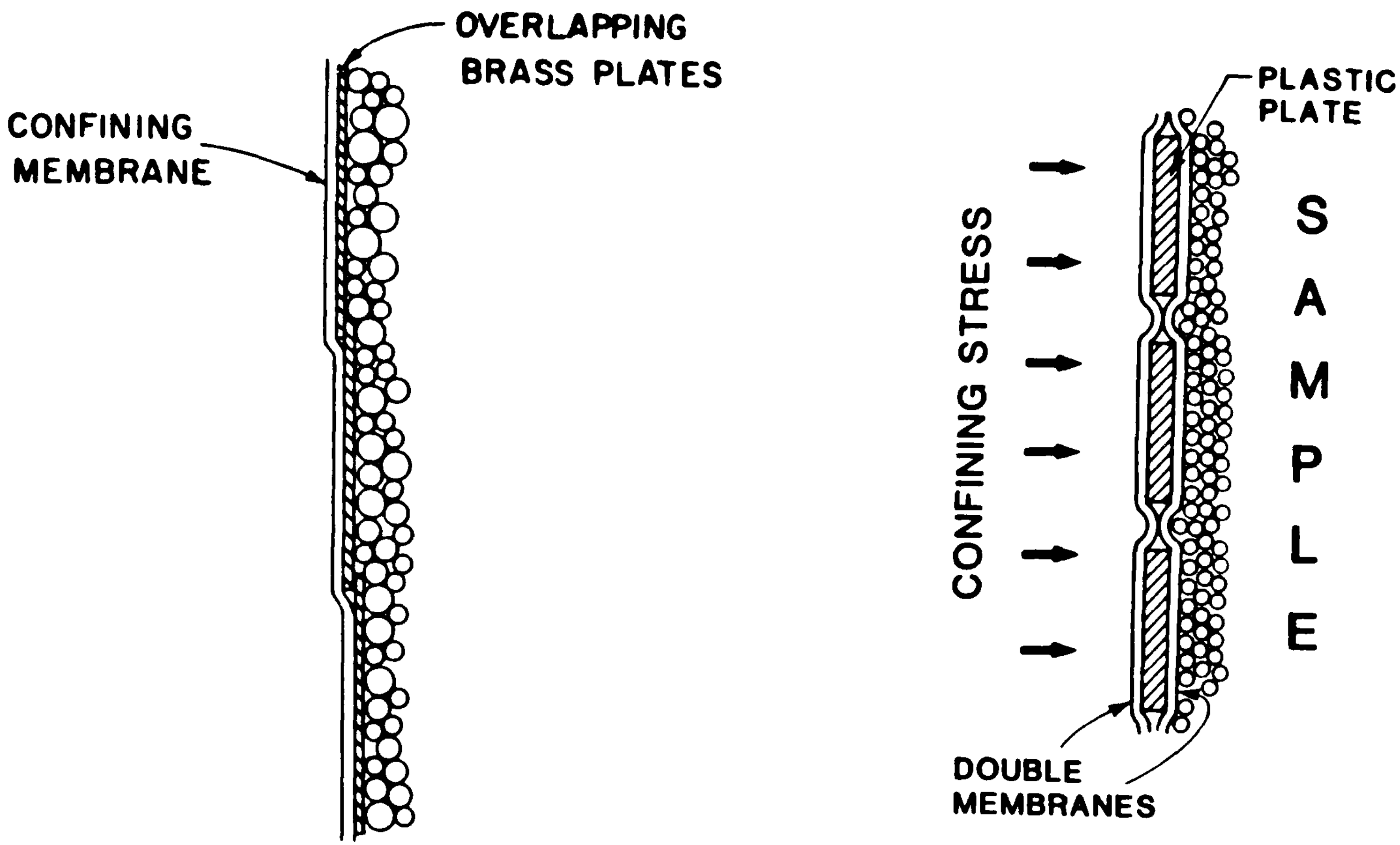
4. "Constant-volume" fully drained simple shear testing.

5. Maintaining a controlled confining cell volume outside of, and surrounding, a triaxial sample in order to preclude variation in membrane penetration.

6. Injection of water into otherwise "undrained" samples to offset pre-determined volume changes due to membrane compliance.

effects. The brass plates were slightly curved in order to conform to the cylindrical sample shape, and overlapped each other slightly. This procedure successfully mitigated compliance effects, but because of friction between the overlapping plates much of the axial load applied to the sample was carried by the stiff plates, negating the usefulness of the procedure. Raju and Venkatamura (1980) used polythene strips between the membrane and the sample instead of brass plates, but in spite of treatment of the strips with silicone grease, friction between the sample and the strips negated the potential usefulness of this method of membrane compliance mitigation.

Similar, unpublished research efforts to mitigate membrane compliance effects were made at the University of California at Berkeley. In this investigation small square plastic plates were fixed with epoxy between a pair of rubber membranes in such a manner that the edges of the plates did not quite contact each other, as illustrated in Figure 2-5(b). The paired rubber



(a) Overlapping Protective Plates

(b) Segmentally-Armored Membrane

Figure 2-5: SCHEMATIC REPRESENTATION OF THE USE OF OVERLAPPING PLATES TO MITIGATE MEMBRANE COMPLIANCE EFFECTS

membranes thus represented a single, segmentally "armored" membrane, which was fully articulated because the plastic squares did not contact each other. This membrane was not susceptible to membrane penetration in the areas where the "armoring" plastic squares occurred. This use of a segmented, armored membrane was found to greatly reduce compliance; the reduction in compliance was found to be roughly proportional to the percent of the total membrane area occupied by the armoring plastic squares. Unfortunately, this armored membrane was also found to have a deleterious effect on sample strength and stress strain behavior, as it contributed an indeterminate fictitious strength and stiffness to measured sample load response, and it was therefore concluded that this approach did not represent a viable means of mitigating membrane compliance effects.

(2) Infilling of external membrane voids:

A number of investigators (e.g., Raju and Venkatamura, 1980, and Wong, 1983) have experimented with the application of either liquid rubber or polyurethane to the outside face of the membrane at the condition of maximum membrane penetration (maximum applied effective confining stress) prior to undrained testing in order to attain a smooth exterior membrane face, as illustrated schematically in Figure 2-6(a). This method has been shown to greatly reduce but not fully eliminate the effects of membrane penetration variation during testing. Unfortunately, however, this procedure effectively results in formation of a much thicker confining membrane which, under applied confining stress, contributes a significant and indeterminate fictitious strength and stiffness to the measured sample load response during testing.

Similar unpublished efforts have involved filling the external sample membrane voids with an infilling material which is, itself, confined by a second membrane as illustrated in Figure 2-6(b). Early efforts involved the

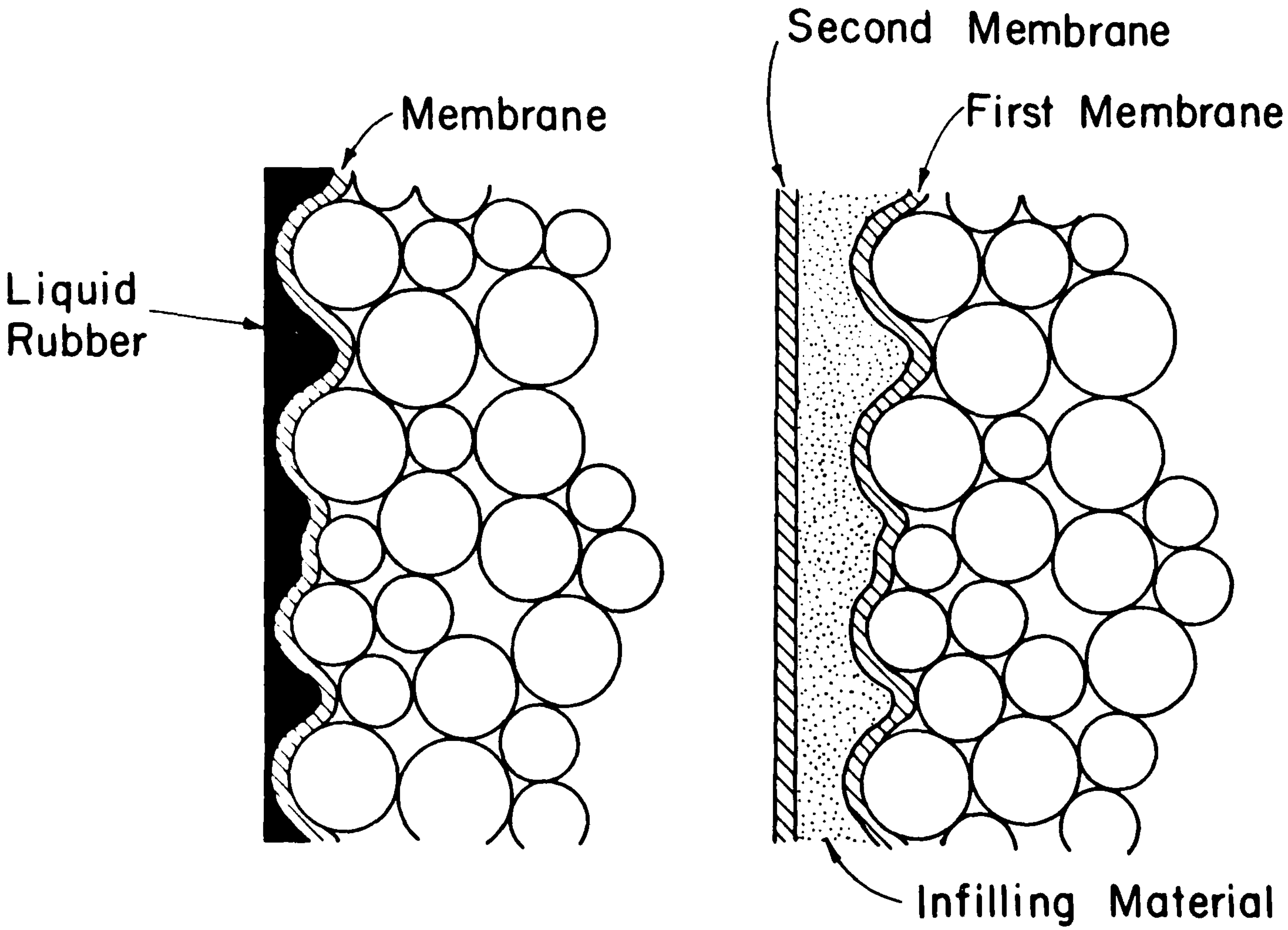


Figure 2-6: INFILLING OF EXTERNAL VOIDS IN THE MEMBRANE PRIOR TO UNDRAINED TESTING

use of clay as an infilling material, and resulted once again in the effective formation of a "thick" composite membrane which significantly affected sample strength and stiffness. An additional investigation currently in progress at a major North American university involves the use of sand as an infilling material between the two membrane layers for large-scale triaxial testing of gravelly soils. In this investigation, a separate back-pressure is being applied to the infilling sand in order to minimize the effective confining stress applied to the sand and thus minimize its contribution to overall sample strength and stiffness. Results of this investigation are not yet available.

(3) Filling of internal peripheral samle voids:

Kiekbusch and Schuppener (1977) experimented with the use of liquid rubber applied to the insides of the confining rubber membranes on triaxial test specimens in order to reduce compliance during testing as shown in Figure 2-7. The interior of the membrane was coated with liquid rubber which penetrated the peripheral sample voids during application of confining pressure and then was allowed to dry prior to testing. This procedure was found to significantly reduce but not fully mitigate membrane compliance effects. Once again, however, this procedure effectively results in formation of a thicker membrane which, under applied confining stress, can influence sample load response.

(4) Constant-volume fully drained simple shear testing:

Pickering (1973) and Moussa (1973, 1975) suggested that drained constant volume cyclic simple shear tests could be used in place of conventional undrained tests, eliminating pore pressure generation and thereby avoiding the effects of membrane penetration. In this procedure, which is similar to that

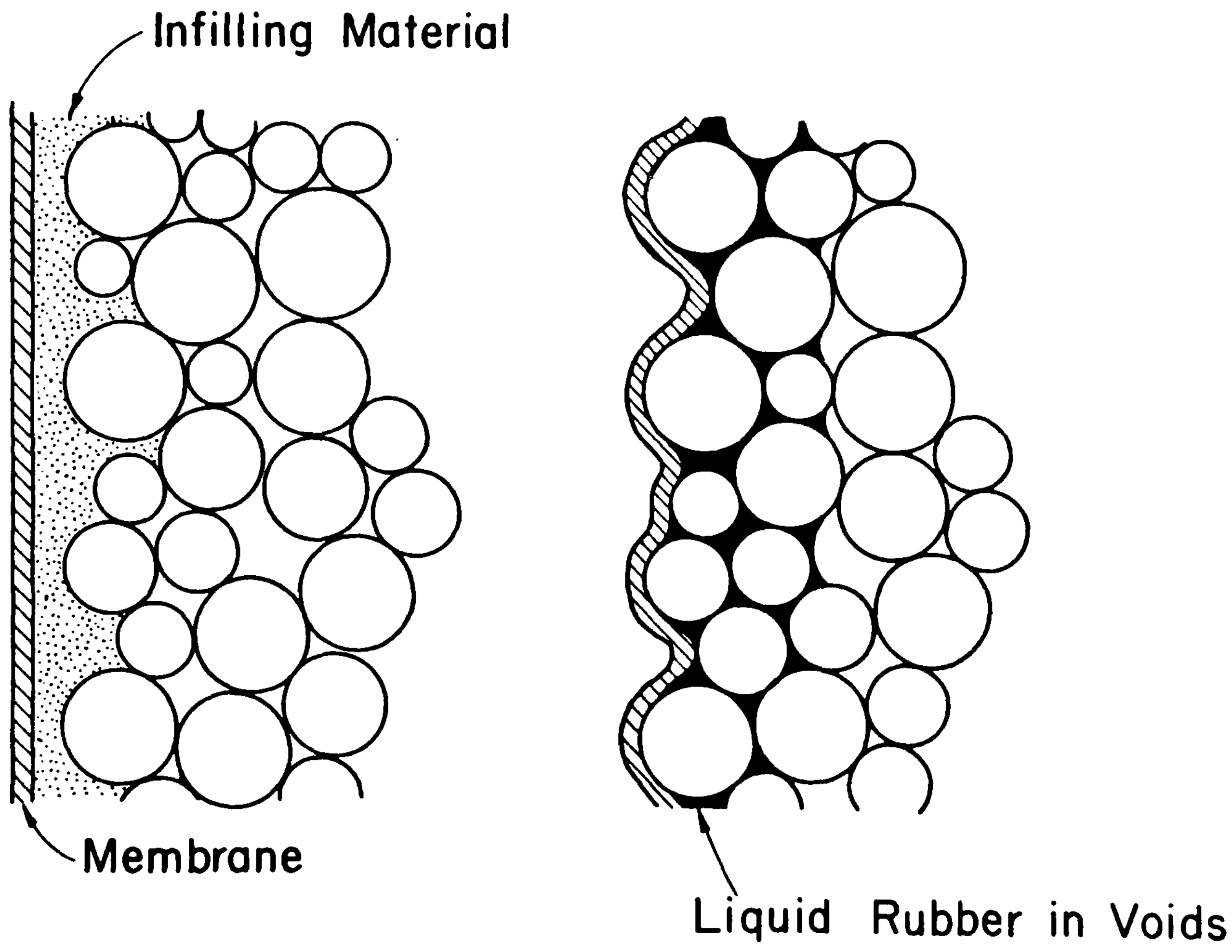


Figure 2-7: FILLING OF INTERNAL PERIPHERAL SAMPLE VOIDS

first used by Bjerrum and Landua (1966) to investigate the behavior of quick clays, cyclic simple shear tests are performed on samples which are kept at constant volume under fully drained conditions by locking the vertical load ram. This testing method is schematically illustrated in Figure 2-8. The soil sample is confined by a spiral-wire-wrapped membrane, so that initial K_o-stress conditions result when the initial vertical load P is applied. After applying the initial vertical load P, the vertical loading ram is rigidly locked in place and the sample is cyclically sheared under fully drained conditions. As the sample densifies under the cyclic shear loading, it begins to "drop away" from the fixed vertical loading ram, resulting in reduction of the sample vertical stress (and a corresponding reduction in lateral stress). The measured reductions in vertical stress are then assumed to reflect the reductions in vertical effective stress which would occur in undrained tests due to pore pressure increases.

Finn and Vaid (1977) compared the results of constant volume drained simple shear tests on Ottawa sand with the results of conventional undrained cyclic simple shear tests on Monterey sand at similar relative densities. Both sands were of similar gradation. The constant volume drained simple shear tests showed a somewhat lower resistence to liquefaction as would be expected if, in fact, the test was successfully mitigating compliance effects, but this conclusion is tentative as some of the difference might be due simply to differences between the two sands. Drained constant volume simple shear tests thus show promise as a possible method of mitigating compliance effects, but further evaluation and verification of the procedure based on comparison with other types of tests for identical samples and identical initial densities is needed. The method has not gained widespread acceptance, probably as a result of testing difficulties associated with simple shear testing. In

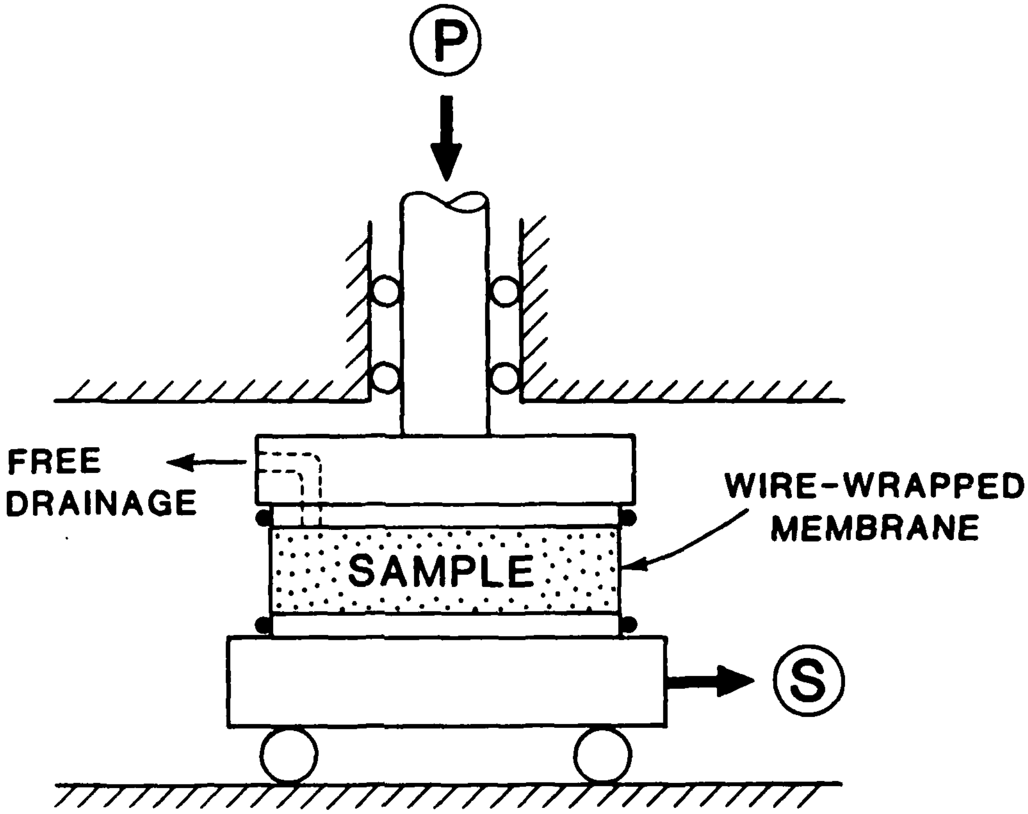


Figure 2-8: CONSTANT-VOLUME FULLY DRAINED SIMPLE SHEAR TESTING (SCHEMATIC)

addition, it should be noted that simple shear testing apparatus tend to be designed for testing of relatively small specimens, so this method is not likely to be easily extended to testing of coarse sands and gravels.

(5) Maintaining a controlled confining cell volume:

Research currently nearing completion at a major North American university involves investigation of the feasibility of preventing membrane compliance effects by controlling the volume of fluid in the confining cell surrounding the soil sample being tested. Similar, unpublished efforts have been undertaken at the University of California at Berkeley. This procedure is illustrated schematically in Figure 2-9. During sample testing, the ingress or egress of the top loading rod into the confining cell chamber is measured, and a volume of confining cell chamber fluid exactly equal to the rod volume is continuously added or removed from the chamber in order to offset the rod-induced chamber volume changes and thus maintain a constant soil sample volume during testing.

Both of the studies of this method performed to date have resulted in the conclusion that this approach is not feasible with current technology. This is because the very fine control of cell fluid volume required generates great difficulties with regard to both sealing and piston friction at the point of load piston ingress, and overall system compliance becomes a major problem as a result of the relatively large volume of cell fluid, difficulties associated with achieving complete elimination of air from the confining cell, and the large surface area involved in confining the cell fluid.

(6) Membrane compliance mitigation by sample injection:

Ramana and Raju (1981) attempted to compensate for sample volume increases due to membrane compliance by injecting additional water into samples during

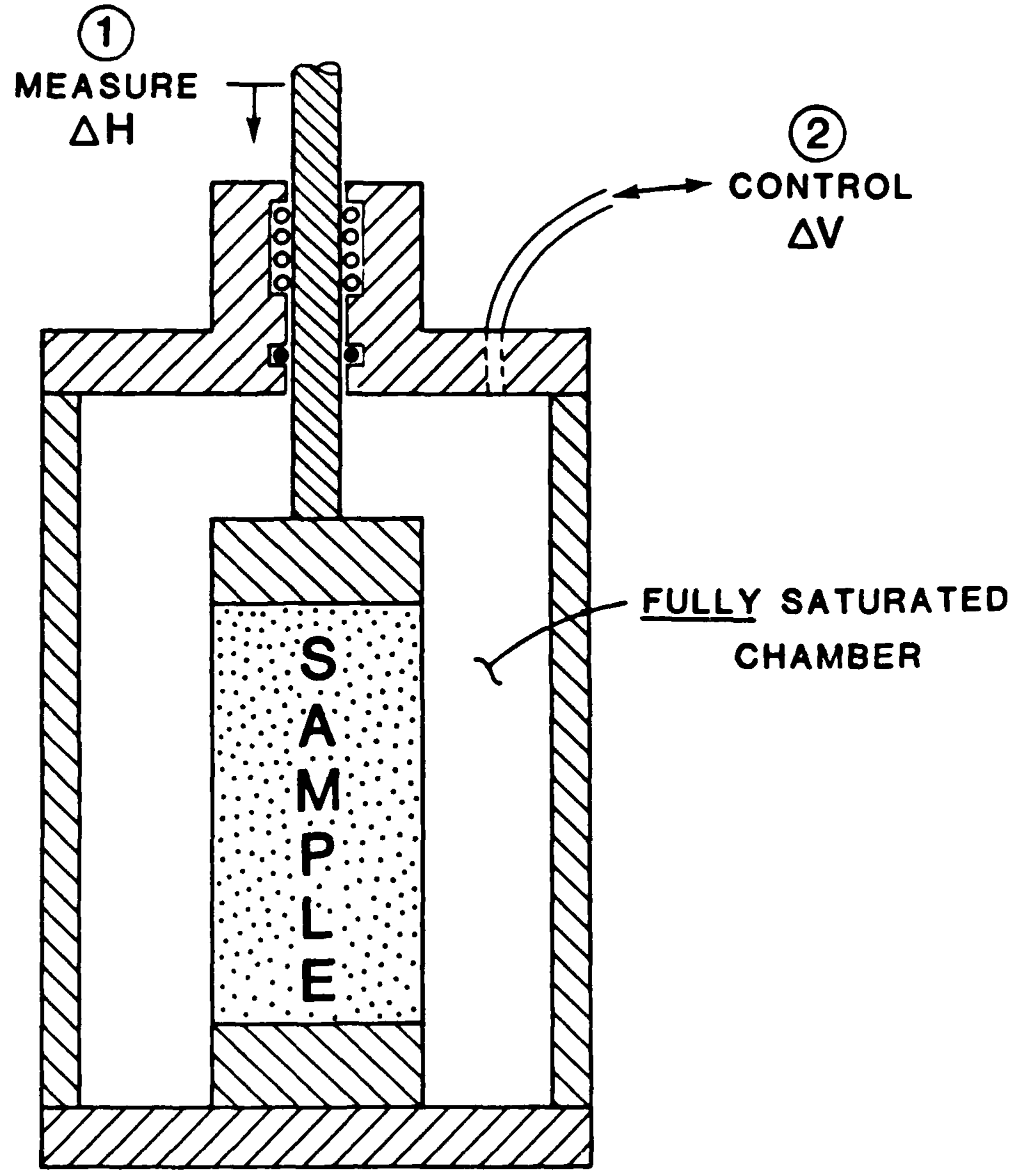
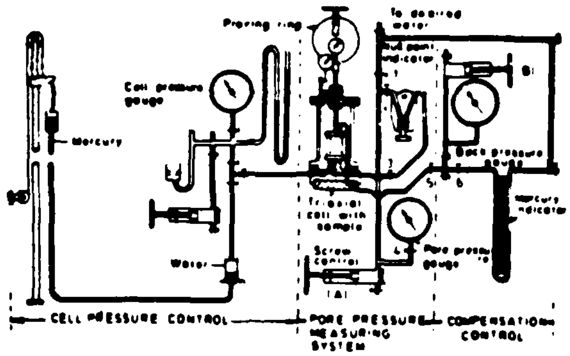


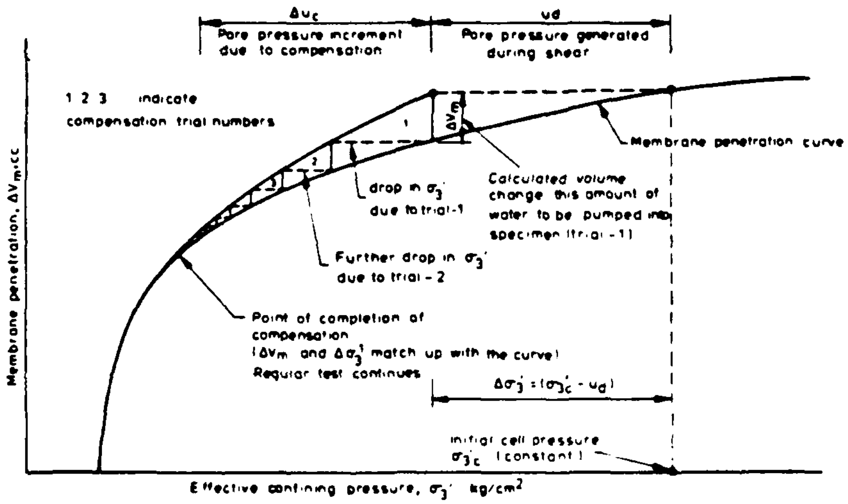
Figure 2-9: SCHEMATIC ILLUSTRATION OF MEMBRANE COMPLIANCE PREVENTION BY CONTROLLING CONFINING CELL VOLUME

undrained triaxial tests. Prior to testing, the unit membrane penetration ($\delta_{v,m}$) was determined using the central rod method, and a compliance curve relating membrane compliance-induced sample volume change to effective confining stress change was established. A sample was then constructed and tested. Figure 2-10(a) shows the test apparatus used, and Figure 2-10(b) illustrates the procedure used to compensate for compliance. The sample was loaded slowly for some time, allowing a pore pressure increase Δu_d to be generated by shearing. After a significant increase in pore pressure had developed, loading was stopped and a volume of water (ΔV_m) was injected into the sample to compensate for membrane compliance as defined by the compliance curve (Trial no. 1 in Figure 2-10(b)). This injection caused an increase in pore pressure, resulting in an additional volume increase, and thus necessitated a second injection of water. This procedure was repeated until convergence with the compliance curve was achieved. At this point loading was resumed.

Figures 2-11 and 2-12 illustrate the results of both monotonic and cyclic loading triaxial tests performed on samples of uniformly graded medium sand with and without implementation of this manual injection-correction procedure. Because the manual multi-step injection procedure was cumbersome, loading proceeded very slowly and iterative correction cycles to convergence with the pre-determined compensation curve were typically initiated only two or three times per loading cycle in cyclic triaxial tests, and only two or three times per test in monotonic loading triaxial tests. As a result, pore pressures were too low and sample strength and stiffness too high throughout much of each "corrected" test. Nonetheless, the procedure greatly increased the rate of pore pressure generation and reduced apparent sample resistance to liquefaction, indicating that compensating injection procedures show promise as a possible means of mitigation of compliance effects.



a) Test Set-Up



b) Stepwise Injection Process

Figure 2-10: RAMANA AND RAJU'S MANUAL INJECTION-CORRECTION PROCEDURE

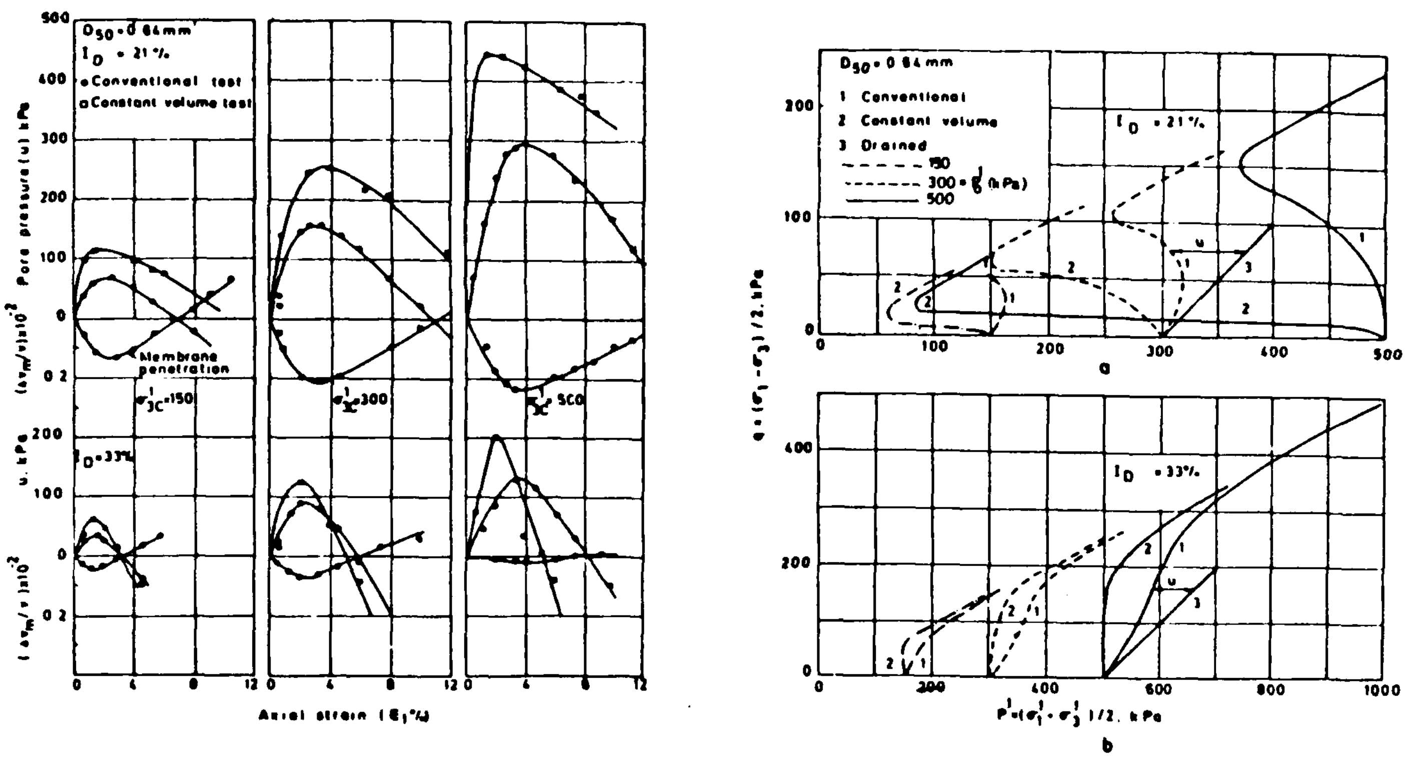
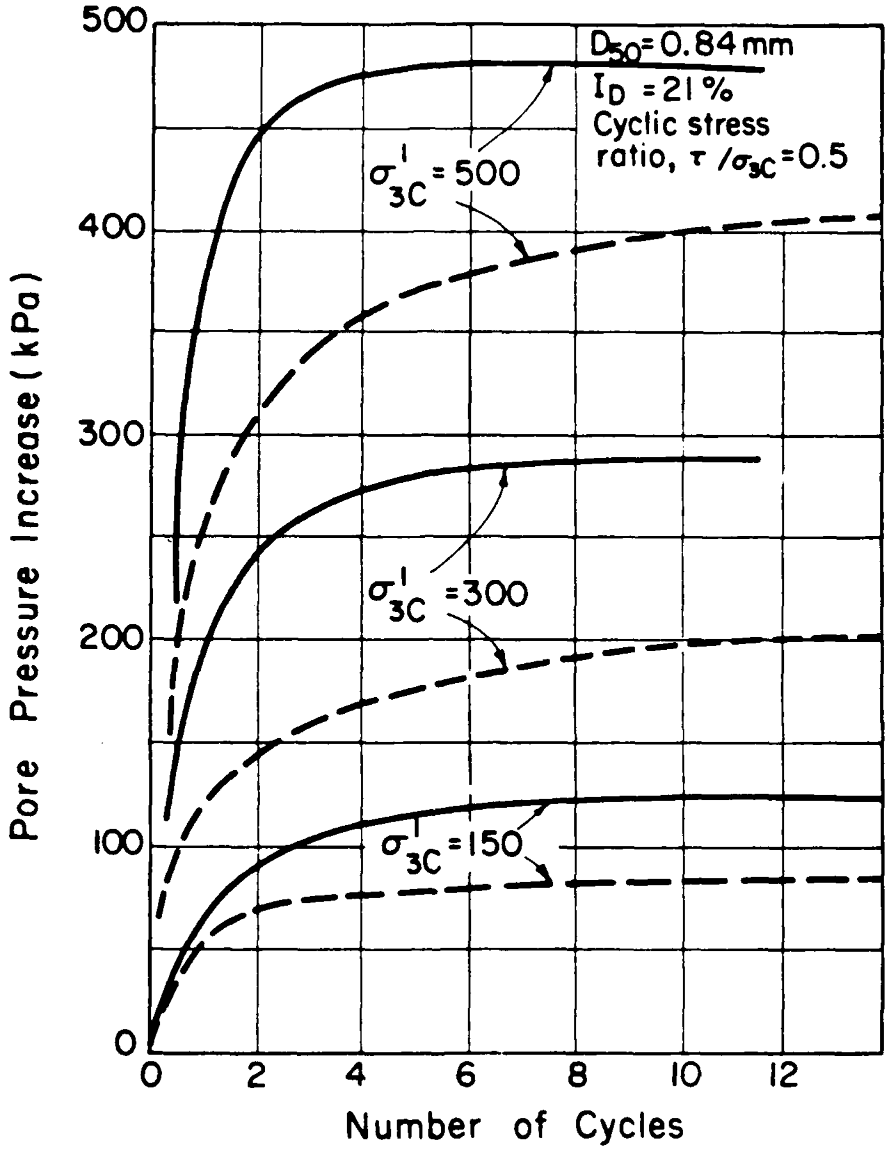


Figure 2-11: UNDRAINED MONOTONIC TRIAXIAL TEST RESULTS WITH AND WITHOUT MANUAL INJECTION CORRECTION



PORE PRESSURE DEVELOPMENT IN ONE-WAY CYCLIC TRIAXIAL TESTS
(After Ramana & Raju, 1981)

Figure 2-12: UNDRAINED CYCLIC TRIAXIAL TEST RESULTS WITH AND WITHOUT MANUAL INJECTION CORRECTION

The principal drawbacks to Ramana and Raju's manual injection-correction attempts appear to be three-fold:

(a) Injection-correction only occurs at irregular and widely spaced intervals during testing and involves a cumbersome iterative process so that sample volume is "correct" only a few times during each test.

(b) The periodic injection process necessitates injection of relatively large water volumes causing relatively large and sudden pore pressure increases which represent a potentially significant "loading" mechanism whose effect on sample behavior is not known (this can be most clearly observed in the stress-path plot for the "constant volume" or "corrected" Type 2 monotonic test of the sample with $\sigma'_{3,i}$ = 500 kPa in Figure 2-11), and

(c) Ramana and Raju were not able to evaluate the influence of the above-mentioned problems, nor were they able to evaluate the effectiveness of the overall mitigation process.

The research described in Chapters 3 and 4 is directed towards overcoming these problems; developing and implementing a computer-controlled injection/removal process capable of fully and continuously mitigating membrane compliance effects throughout the course of undrained monotonic or cyclic triaxial tests.

2.3 Further Research Needed:

In spite of recent progress, no completely reliable procedures are currently available either for mitigation of membrane compliance effects in undrained testing of saturated soils, or for interpreting the results of conventional undrained liquefaction tests to correct for compliance effects. Until a reliable laboratory technique is developed for conducting tests on coarse-grained soils in which membrane compliance effects are successfully eliminated, it will not be possible to (1) determine the true strength of such soils under undrained conditions; (2) determine the effectiveness of approximate procedures for mitigating membrane compliance effects, such as treatment of membranes with liquid rubber or the use of constant volume simple shear

tests; or (3) evaluate the reliability of theoretical and/or empirical methods for post-test correction of conventional test data for membrane compliance effects. The approach of minimizing the impact of compliance effects by testing large diameter samples limits the capacity of most conventional apparatus to performing representative tests on only fine sands and silts, and even the few very large scale facilities available are not fully suitable for undrained testing of gravels. In fact, at the present time it is not possible to perform representative undrained tests on very coarse soils such as gravels to evaluate their true liquefaction characteristics.

There is a need to develop testing procedures and apparatus which successfully mitigate membrane compliance effects during testing without inducing new problems such as excessive membrane stiffness. Mitigation of compliance must also be continuous and complete throughout the test in order to ensure correct results in view of the inter-relationships between soil resistance, cyclic or monotonic strain, and pore pressure generation. It is highly desirable that such testing apparatus be economically available, and that testing procedures represent a minimum level of difficulty. These procedures should be suitable for small-scale testing of coarse sands, and should allow for truly representative undrained testing of gravels in large-scale test facilities.

Drained constant volume simple shear tests represent one potential method for mitigation of compliance effects, but this requires verification based on comparison with other test types. In addition, the method has not gained widespread acceptance, probably due to testing difficulties, and appears unlikely to represent a suitable method for large-scale testing of coarse soils.

It appears at this time that the best possible method to completely eliminate the effects of membrane compliance in soil testing would consist of

accurately measuring the magnitude of volumetric changes due to membrane penetration as a function of confining stress, and then continuously compensating for these changes by controlled injection or removal of an appropriate volume of water. Accordingly, this approach has been selected for evaluation and implementation in these studies.

3.0 DEVELOPMENT OF A COMPUTER-CONTROLLED INJECTION REMOVAL SYSTEM FOR MEMBRANE COMPLIANCE MITIGATION

3.1 General Overview:

The membrane compliance mitigation methodology selected for development and implementation in these studies consists of first pre-determining the volumetric magnitude of membrane compliance for a given soil as a function of sample effective confining stress, and then using a computer-controlled process to continuously inject or remove water from the sample during undrained testing in order to exactly offset the volumetric error induced by membrane compliance. In order to implement this technique: (a) it was necessary to demonstrate that compliance could be reliably pre-determined, (b) a computer-controlled injection system had to be developed, and (c) testing problems associated with implementation of the injection-mitigation process had to be resolved. Completion of these three steps are discussed in Sections 3.2, 3.3, and 3.4, respectively.

3.2 Pre-Determination of Membrane Compliance:

3.2.1 General:

In order to implement the proposed injection-mitigation techniques, it was first necessary to demonstrate (a) that volumetric membrane compliance could be reliably pre-determined prior to testing, (b) that it is a direct and repeatable function of sample effective confining stress, and (c) that it can be reliably characterized in such a manner that the computer-controlled injection/removal process can be based on monitoring changes in sample effective confining stress. Studies of factors affecting volumetric membrane compliance are currently in progress at Stanford University (Anwar, 1986), and the following is a brief summary of these studies.

Numerous investigators (e.g., El-Sohby, 1964; Frydman et al., 1973; Kiekbush and Shuppener, 1977; Raju and Venkatamura, 1980; Baldi and Nova, 1984; etc.) have shown that volumetric membrance compliance magnitude is a function of sample effective confining stress (σ_3'), and that the relationship between compliance volume and σ_3' has a curvilinear relationship as shown in Figure 3-1. This figure shows membrane compliance-induced volume change per unit area of membrane (δV_m; cc/cm^2) for Monterey 16 sand at a relative density of 60%. A description and gradation curve for this uniformly graded medium sand are presented in Section 4.1. It has also been demonstrated that the relationship between δV_m and $\log_{10}(\sigma_3')$ is essentially linear over the range of interest as is again illustrated for Monterey 16 sand in Figure 3-2. The slope of this semi-log compliance function (δV_m per log cycle change in σ_3') will hereafter be referred to as "normalized unit membrane penetration" (S), and will be used to characterize volumetric compliance for a given soil.

For large-scale triaxial testing, membrane compliance can be measured by performing drained isotropic compression tests on saturated samples and directly measuring sample axial and radial compression as discussed in Section 2.1.1. For samples less than 6 inches in diameter, radial sample strains cannot be measured directly with sufficient accuracy, and the indirect "two-sample scale model" method proposed in Section 2.1.2 is strongly recommended. This indirect method was used in studies of compliance at Stanford University.

3.2.2 Factors Affecting Membrane Compliance:

This section presents a discussion of factors affecting membrane compliance, and discusses empirical relationships for estimation of compliance magnitude based on these factors. It should be emphasized, however, that this discussion of empirical relationships is intended primarily as a framework for considering the relative influences of various factors: the <u>best</u> way

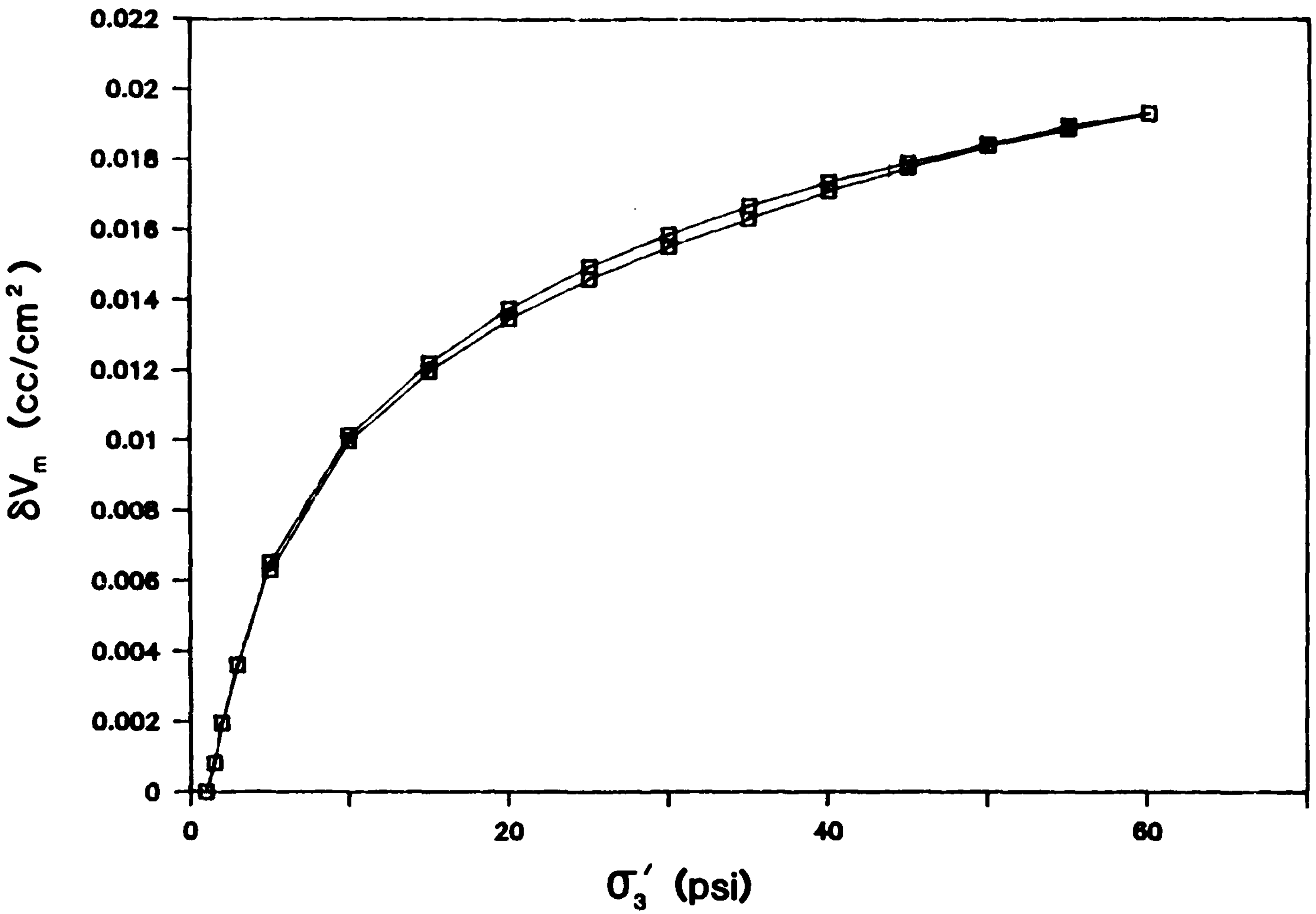


Figure 3-1: UNIT MEMBRANE COMPLIANCE vs. EFFECTIVE CONFINING STRESS FOR MONTEREY 16 SAND AT D_R = 60%

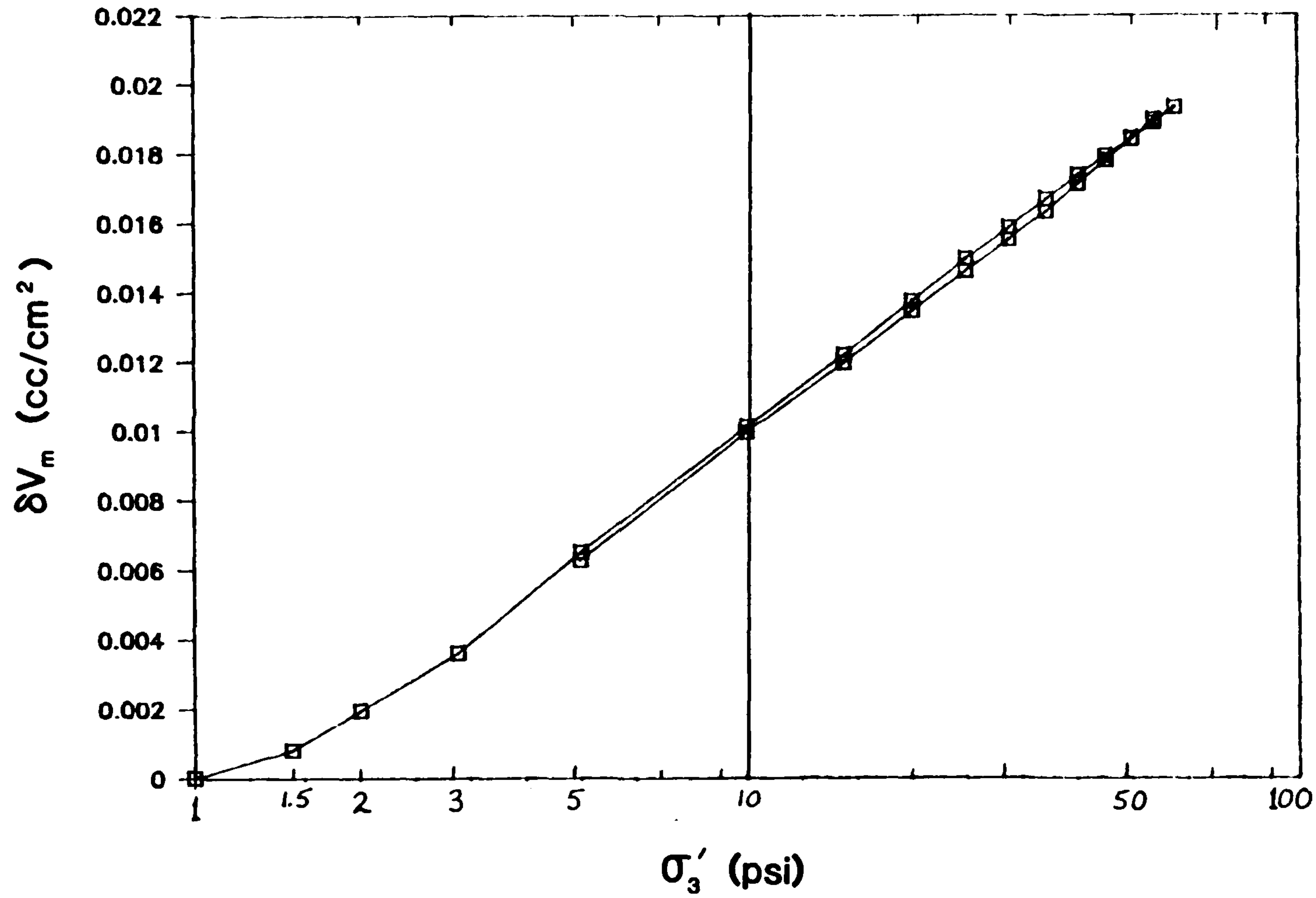


Figure 3-2: UNIT MEMBRANE COMPLIANCE vs. LOG_{10} OF EFFECTIVE CONFINING STRESS FOR MONTEREY 16 SAND AT D_R = 60%

to pre-determine volumetric membrane compliance for a given soil at a given density is to measure it by constructing and testing similar samples prior to actual undrained testing.

A number of factors were considered for study as potentially affecting the volumetric magnitude of membrane compliance, in additon to effective confining stress, and these were: (a) soil grain size and grain size distribution (gradation), (b) soil density, (c) soil particle shapes or angularity, (d) soil fabric or method of sample preparation, and (e) membrane thickness or stiffness.

The most important of these factors was found to be sample gradation, a finding in agreement with earlier investigators (Ramana and Raju, 1982). It was, further, found that all other factors considered were relatively insignificant as compared to the overwhelming influence of sample grain size and grain size distribution. Literature review showed that previous investigators had consistently correlated unit membrane compliance magnitudes with mean sample grain size (D_{50}). It was also found that virtually all soils examined by previous investigators had been uniformly graded soils.

Studies at Stanford examined both well graded and gap graded soils, in addition to uniformly graded soils. It was found that unit membrane compliance magnitude was much better correlated with smaller particle sizes (D_{20}) than with the mean grain size (D_{50}). This is not surprising, as membrane penetration is a phenomenon associated primarily with inter-grain void spaces, and studies of both flow and "soil filter" characteristics have long recognized that finer soil particles than the mean grain size control the characteristics of these inter-particle voids. It was also found that sample gradation exerted a significant influence in addition to grain size as characterized by D_{20}; for two or more soils with similar D_{20} grain sizes, both gap

graded and well graded soils exhibited significantly lesser normalized unit membrane penetration.

An empirical equation was developed for the estimation of normalized unit membrane penetration as a function of sample gradation as

$$S = \{(0.0009)[\log_{10}(D_{20} + 2.0)]^{3.8} + 0.0005\} \cdot F_1 \cdot F_2 \qquad (3\text{-}1)$$

where S = normalized unit membrane penetration (cc/cm^2 per log cycle change in σ_3'),

D_{10}, D_{20}, D_{50} = soil grain sizes (mm), and

$$F_1 = \left(\frac{D_{10}}{D_{20}}\right)^{0.33} \quad \text{and} \quad F_2 = \left(\frac{D_{20}}{\sqrt{D_{10}}}\right)^{-0.25}$$

Without the factors F_1 and F_2, this equation is directly applicable to uniformly graded soils. The factors F_1 and F_2 represent the effects of potentially non-uniform grain size distribution, and thus extend the relationship to consideration of non-uniformly graded soils (e.g., well graded and gap graded soils).

Figure 3-3 shows a plot of S vs. D_{50} for a group of soils tested by five different sets of investigators. A number of these soils have S-values considerably lower than those suggested by the approximate relationship for uniformly graded soils shown by the dashed line in this figure. Most of the soils represented in Figure 3-3 are fairly uniformly graded; however, most of the soils whose S-values plot significantly below the dashed curve are not uniformly graded.

All of the non-uniformly graded soils in Figure 3-3 have S-values which correlate significantly better with D_{20} than with D_{50}, as do many of the fairly uniformly graded soils. Further improvement in this correlation can be achieved by invoking the factors F_1 and F_2 from Equation 3-1. Figure 3-4 shows a plot of S vs. D_{20} for the same soils as were represented in Figure 3-3.

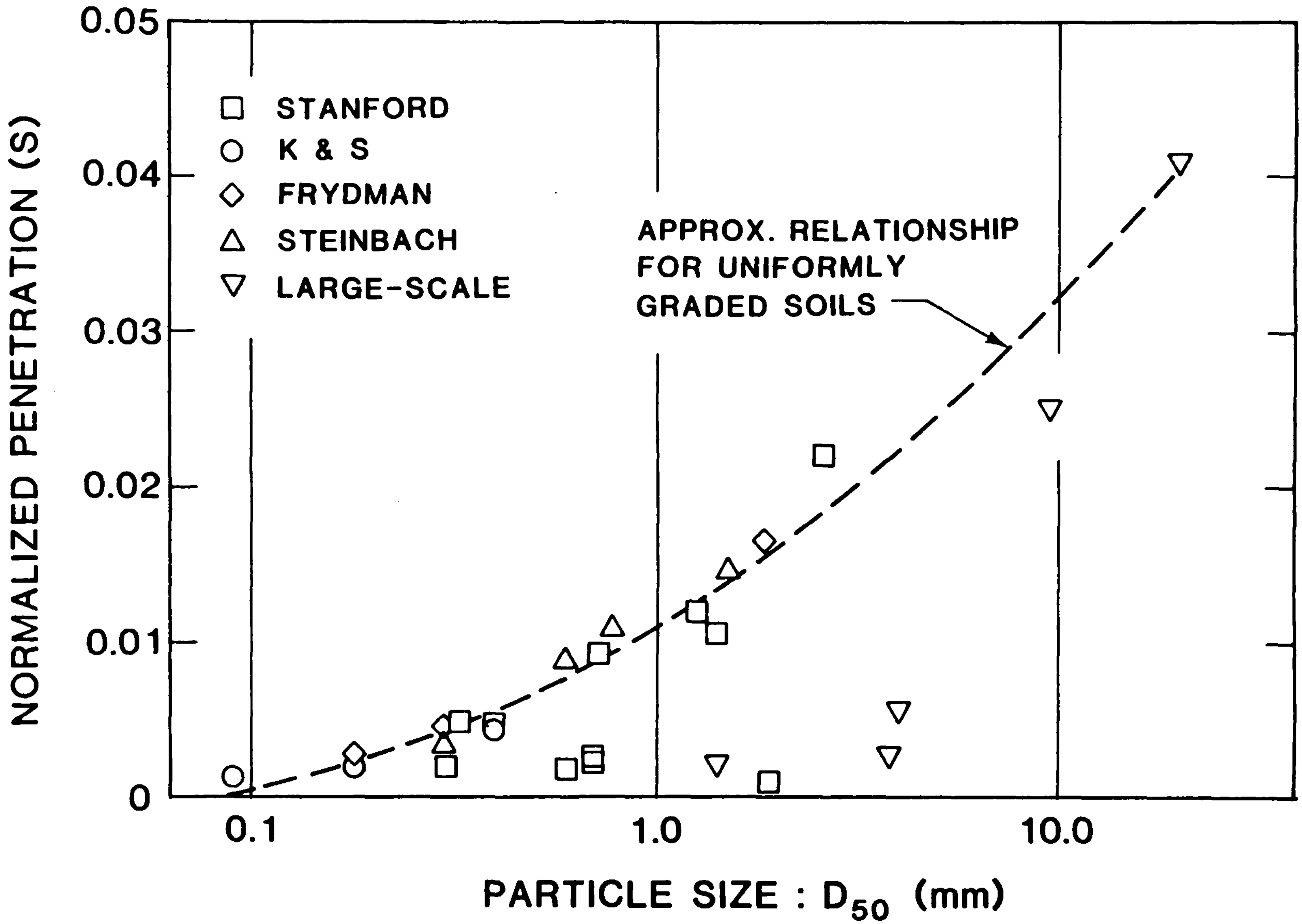


Figure 3-3: NORMALIZED UNIT MEMBRANE PNETRATION (S) vs. D_{50}

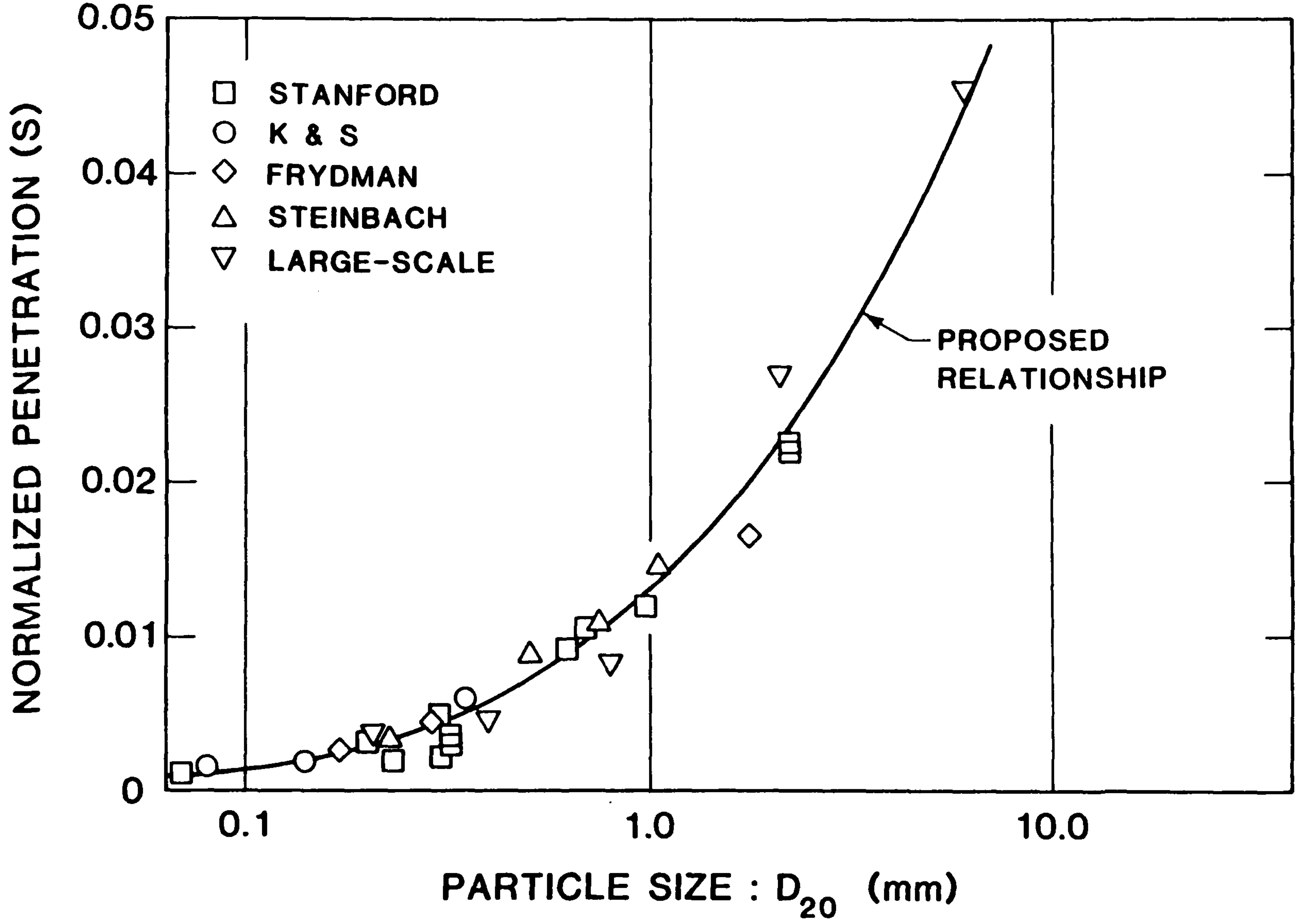


Figure 3-4: NORMALIZED UNIT MEMBRANE PENETRATION (S) vs. D_{20} WITH CORRECTIONS FOR NON-UNIFORM GRADATION

In this figure, the S-values of all non-uniformly graded soils have been normalized by dividing by the factors F_1 and F_2. The solid line in this figure represents the relationship proposed in the first term of Equation 3-1 (without F_1 and F_2). As shown in Figure 3-4, this empirical relationship provides a significantly improved basis for estimation of S than earlier relationships which were based primarily on D_{50} and which neglected the potential influence of non-uniform sample gradations.

Investigation of the influence of sample density on unit membrane compliance showed this factor to have a fairly consistent but relatively minor effect, a result once again supported by the findings of earlier researchers. As an example of this, Figure 3-5 shows unit membrane compliance curves for five samples of Monterey 16 sand tested at relative densities of 45%, 50%, 55%, 60%, and 65%. It is suggested that the relationship of Equation 3-1 is most appropriate for soils of medium density, and that some minor adjustment be made for very loose or very dense soils.

Investigation of the influence of particle grain shapes or angularity showed this factor to exert no significant influence on unit membrane penetration. Samples of essentially identical gradation prepared to the same relative density, but having either well-rounded or highly angular particle shapes exhibited very similar unit membrane penetration characteristics.

Soil fabric (and/or method of sample preparation) was a potentially important factor because soil fabric can be altered during the course of testing. This meant that if soil fabric had a significant influence on unit membrane penetration, then reliable pre-determination of volumetric membrane compliance as a basis for control of an injection-mitigation process would not be feasible. Fortunately, soil fabric or method of sample preparation were found to have no significant influence on unit membrane penetration. Samples

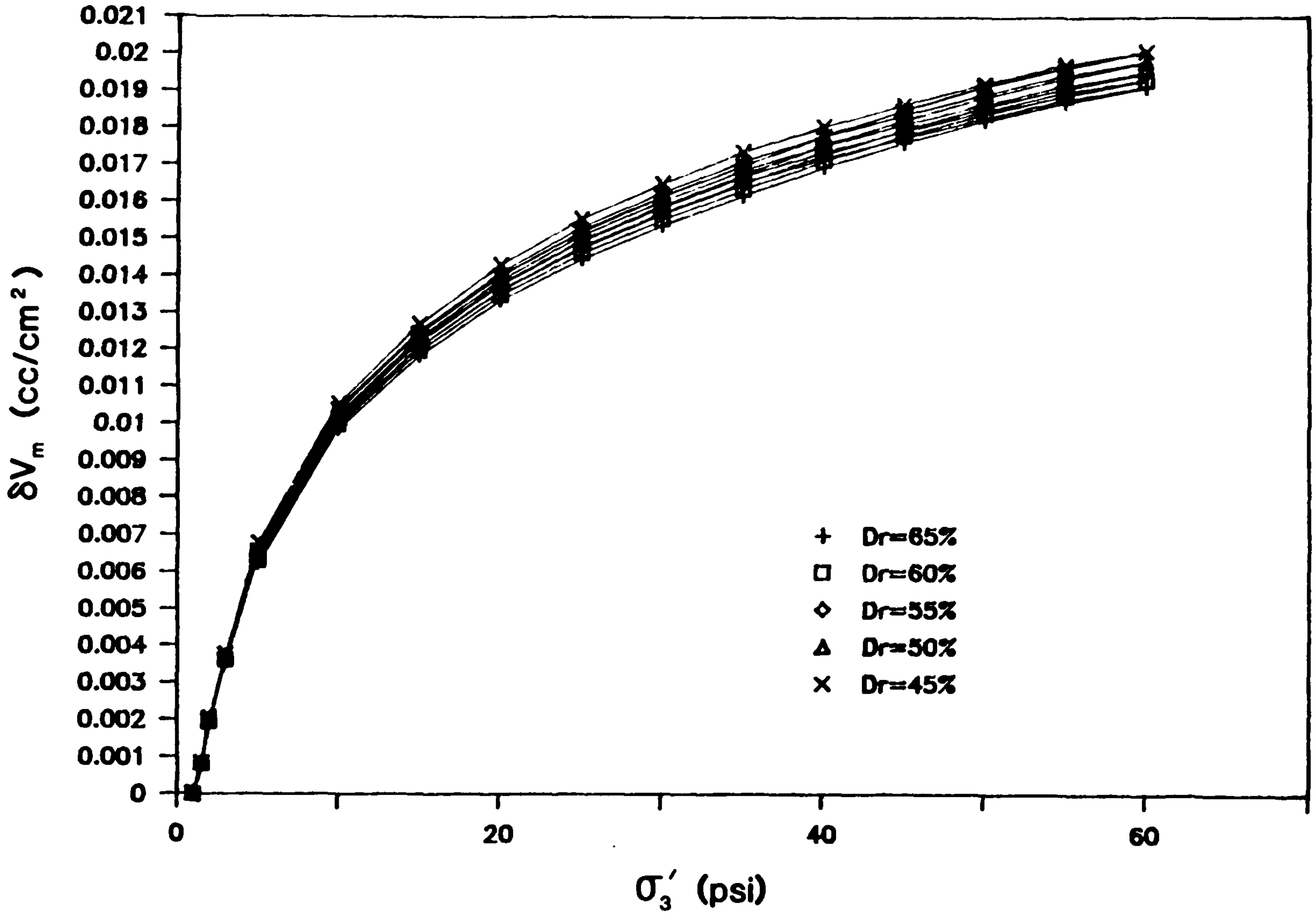


Figure 3-5: UNIT MEMBRANE COMPLIANCE vs. EFFECTIVE CONFINING STRESS FOR MONTEREY 16 SAND OVER A RANGE OF RELATIVE DENSITIES

of the same soil, prepared to the same density but by different methods (either dry pluviation or moist tamping) were found to have essentially identical membrane compliance characteristics. In addition, a number of samples were fabricated and tested for unit membrane compliance, then were cyclically loaded under undrained conditions to full initial liquefaction (pore pressure ratio r_u = 100%), and were then reconsolidated and re-tested for membrane compliance characteristics. Post-liquefaction compliance characteristics were found to be the same as pre-liquefaction characteristics. An example of this is shown in Figure 3-6, which shows pre- and post-liquefaction membrane compliance measurements of samples of fine Ottawa sand at relative densities of D_R = 50%.

The final factor considered, membrane thickness or stiffness, has been studied by previous investigators. Experimental investigations have shown that the use of latex membranes of different thicknesses has almost no effect on unit membrane compliance (Ramana and Raju, 1982). This result was verified at Stanford University by testing several soils confined in latex triaxial membranes of 0.008-, 0.014-, and 0.028-inch thickness. This effective quadrupling of membrane thickness was found to alter unit membrane compliance by less than 5% for sandy soils. The relative unimportance of membrane thickness and stiffness has also been demonstrated theoretically by Molenkamp and Luger (1981) and Baldi and Nova (1984). Molenkamp and Luger used a fairly complex visco elastic-plastic constitutive model for the behavior of latex in their theoretical studies, and showed that creep effects and long-term strain softening of latex is also likely to affect membrane compliance. This effect, which is relatively minor, was also noted during the experimental investigations at Stanford University, and it is recommended that the best method for pre-determination of membrane compliance is achieved by measuring compliance

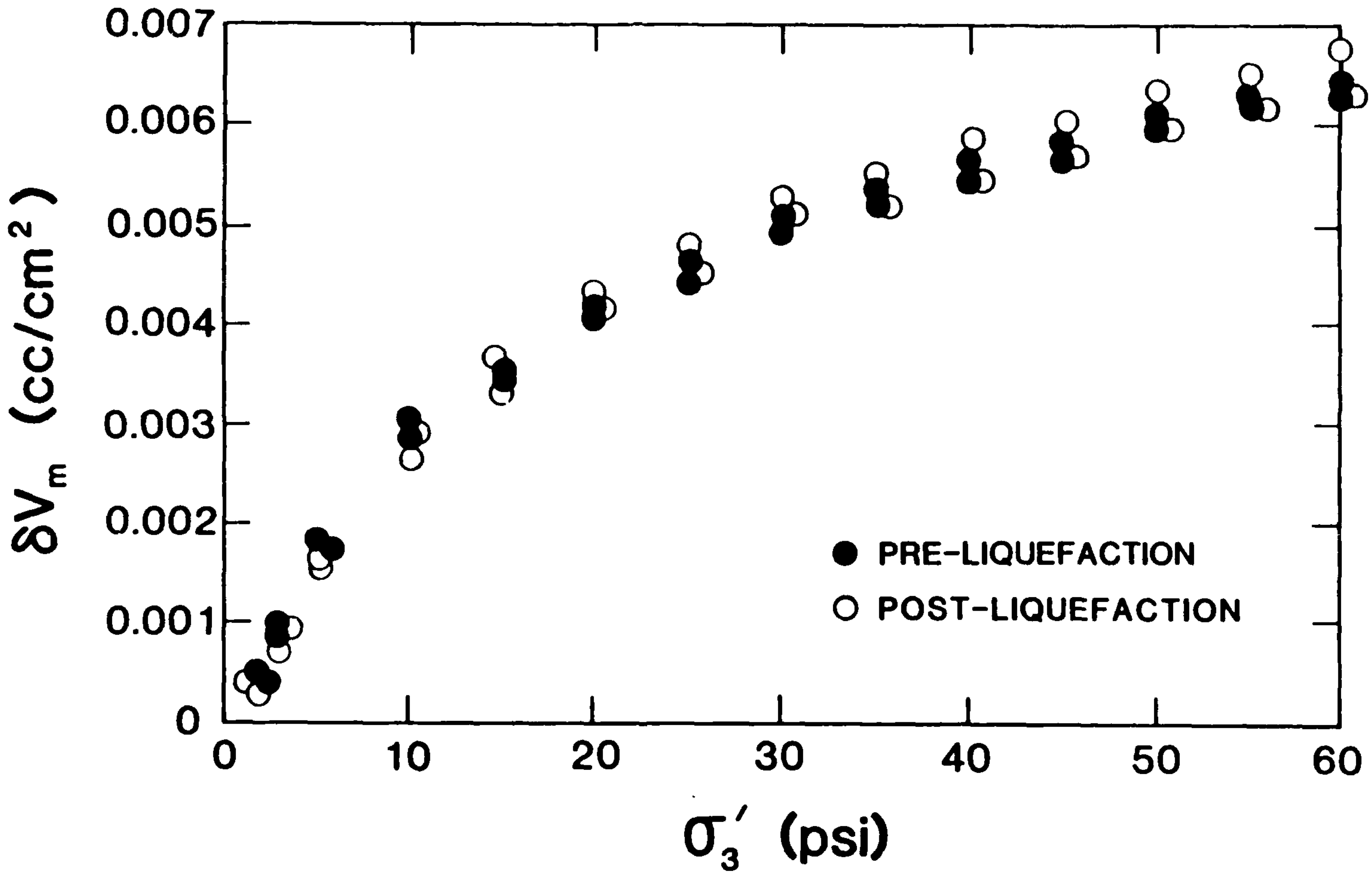


Figure 3-6: PRE- AND POST-LIQUEFACTION MEMBRANE COMPLIANCE CURVES FOR FINE OTTAWA SAND AT D_R = 50%

on samples left standing for approximately one hour under the initial effective sample confinning stress to be used in subsequent undrained testing. This "ageing" of the compliance measurement samples promotes "pre-stretching" of the sample membranes.

All of these studies of factors affecting unit membrane compliance (δV_m) indicate that volumetric membrane compliance is a direct and repeatable function of sample effective confining stress, that it can be accurately and reliably pre-determined for a given soil of given density prior to undrained testing, and that such pre-determination of volumetric membrane compliance represents a viable basis for control of injection-mitigation during subsequent undrained testing.

3.3 Development of a Computer-Controlled Injection/Removal System:

Figure 3-7 presents a schematic illustration of the microcomputer-controlled injection/removal system developed for mitigation of membrane compliance effects during undrained triaxial testing. The injection mitigation system has two major components: an IBM PC-AT microcomputer with a Metrabyte A/D conversion board, and a GDS digital pressure/volume controller which was modified to bypass its internal circuitry in order to provide for direct control of its injection piston by the PC-AT microcomputer.

This system requires only a single connection (at valve A in Figure 3-7) to the sample pore pressure lines of a conventional triaxial testing system. The injection system has a self-contained pore pressure transducer and so is able to directly monitor changes in effective ssample confining stress without any need for interaction with other test control or data acquisition systems. An optional connection to the LVDT used to monitor sample radial deformations is also shown in Figure 3-7, and this permits modification of injection/removal control based on changes in sample geometry (membrane surface area

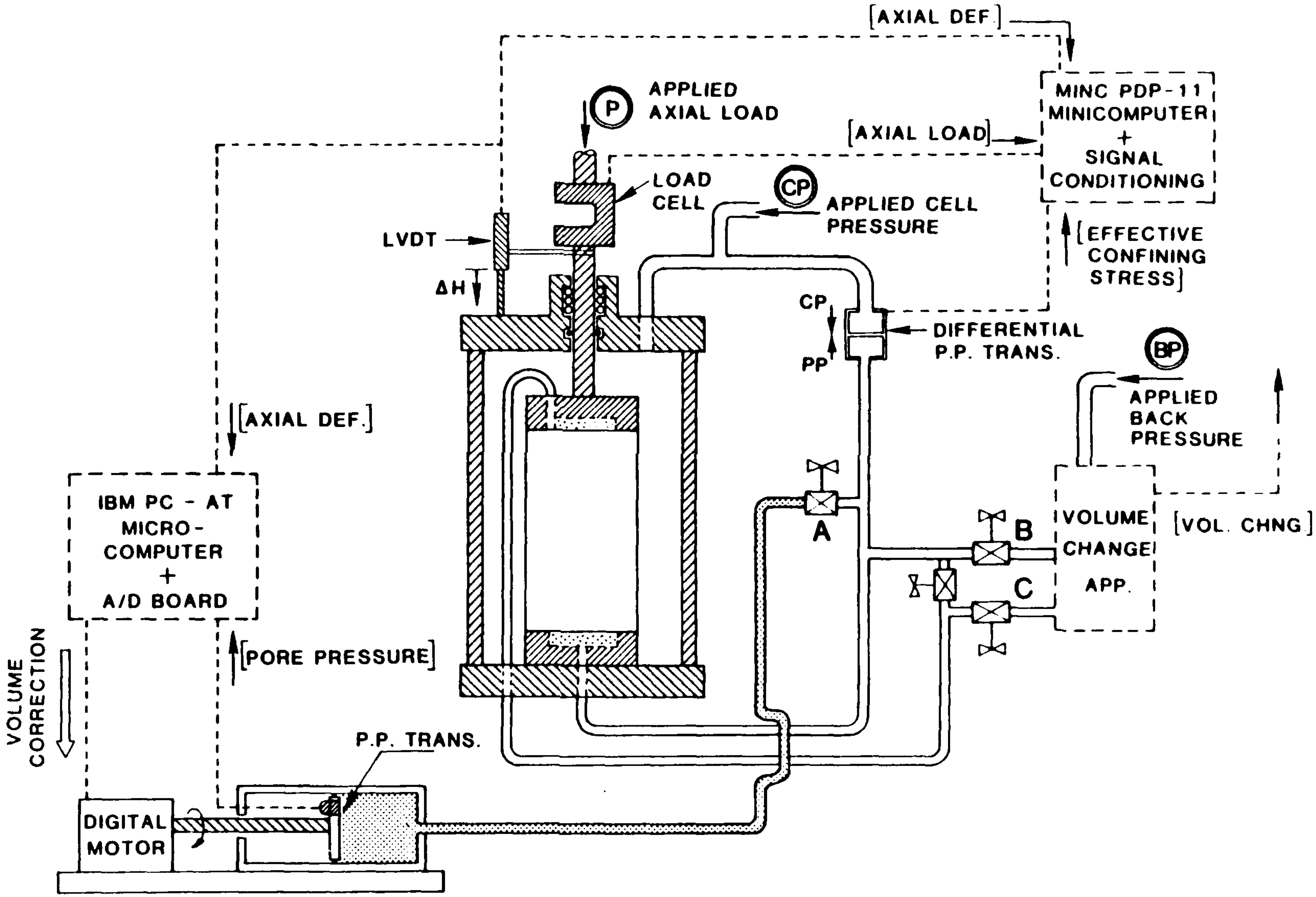


Figure 3-7: SCHEMATIC ILLUSTRATION OF COMPUTER-CONTROLLED INJECTION/REMOVAL SYSTEM FOR MEMBRANE COMPLIANCE MITIGATION DURING UNDRAINED TRIAXIAL TESTING

changes can be directly calculated from axial deformations based on assumed right-cylindrical deformation and zero net sample volume change). In practical application, however, these membrane surface area changes are not significant and this connection may be omitted. This injection-mitigation system, with its single, simple pore pressure line connection, is designed for rapid and easy connection to any small-scale triaxial testing system.

The GDS digital pressure/volume controller consists of a hydraulic injection/removal piston driven by a digital motor. The injection piston has its own internal pore pressure transducer. The GDS controller is self-programmable and its internal electronics are designed to permit programmable control of pressures. The GDS controller was modified in such a manner that its own internal electronics could be bypassed, permitting direct control of the digital motor by the PC-AT microcomputer, and direct reading of the internal pore pressure transducer by the microcomputer (via the A/D conversion board). The system also allows for use of the GDS system electronics for manual control of the injection piston during test set-up.

The digital motor-driven injection piston can inject or remove water from a sample at a rate of up to 1.0 cc/sec, with an advertised accuracy of ± 0.0005 cc. System compliance was found to adversely affect accuracy, but it was judged that actual injection volume accuracy was better than ± 0.002 cc. This level of accuracy and the maximum injection rate are both more than sufficient for injection-mitigation of membrane compliance effects in conventional (small-scale) triaxial testing.

Implementation of computer-controlled injection-mitigation during undrained testing involved first pre-determining the unit membrane compliance correction curve (δV_m vs. σ_3') for a given soil of given density. For conventional triaxial samples (with diameters of less than 6 inches), the "two-

sample scale model" procedure suggested in Section 2.1.2 is recommended. It is further recommended that the two "scale model" samples be subjected for at least one hour to the initial effective confining stress which will be applied to the sample to be subsequently tested with injection mitigation, in order to pre-stretch the scale model sample membranes prior to measurement of compliance. The resulting unit membrane compliance curve is then processed to evaluate the normalized unit membrane penetration (S) in units of cc per cm of membrane area per log-cycle change in σ_3'.

A sample to be subjected to undrained testing with implementation of injection-mitigation is then fabricated, saturated, and consolidated to the desired initial sample confining stress conditions. The unit membrane penetration value (S) is then entered into the microcomputer, along with initial sample height and diameter (for calculation of total exposed membrane surface area), and the initial lateral effective sample confining stress (σ_3'). Once instructed to begin injection-mitigation, the computer-controlled system monitors all subsequent changes in $\bar{\sigma}_3$, and continuously injects or removes a controlled volume of water to exactly offset the volumetric error induced by membrane compliance. Cycles of pore pressure reading, calculation, and injection/removal of appropriate volume can typically be performed by this system at a rate of several cycles per second.

3.4 Testing Problems in Implementation of Injection-Mitigation:

A number of practical problems had to be overcome in implementing the computer-controlled injection-mitigation process developed. The first of these was a tendency for the injection volume control to become unstable at low effective confining stresses (where injection/removal volumes are large per unit change in σ_3'). This instability was found to be the result of pressure waves set up within the injection piston itself as a result of the abrupt

piston motions in a small, confined chamber. These pressure waves were adequately damped during transmission through the injection line, and so had no adverse influence on sample behavior. The peak high and low pressure pulses in the injection piston itself were, however, randomly read by the internal pore pressure transducer and caused injection or removal of correspondingly large volumes of water at low effective confining stresses. This resulted in a tendency for sample injection volumes to oscillate wildly, though with an approximately correct mean value, at low σ_3'.

This problem was solved by modifying the system control software so that injection or removal of water to offset some compliance-induced change in volume (as based on some perceived change in σ_3') was accomplished in a series of at least five increments, with additional pressure readings taken periodically to "smooth out" perceived high and low pressure peaks and troughs. The first increment of each correction series injects or removes approximately one-half of the volume adjustment called for by any perceived pressure change, and subsequent iterations rapidly converge on the correct volume. As several iterations are performed each second, it is judged that approximately 90% to 105% of membrane compliance-induced volume change is continuously offset at all times during testing at the rates of loading described in Chapter 4.

A second problem encountered was the fact that the GDS digital controller had a level of internal system volumetric compliance which was at least moderately significant relative to the small volumes of membrane compliance-induced volumetric errors to be offset. This system compliance, which is attributed to minor expansion and contraction of the injection cylinder and deformation of the piston seal, was measured as a function of internal piston pressure. System compliance was found to be a repeatable function of internal piston pressure, with little hysteresis or difference between compliance

during internal pressure loading or unloading cycles. The system compliance curve was programmed into the PC-AT microcomputer, and all injection/removal volumes were continuously adjusted accordingly. It should be noted that the system compliance curve was valid only for conditions corresponding to full cylinder saturation, and that achieving this full saturation was a difficult component of the test procedure. With appropriate allowance for system compliance, it was judged that injection/removal volume accuracy achieved was consistently better than ± 0.002 cc.

A final testing problem considered was the potential difficulty in maintaining a uniform internal sample pore pressure field, as injection or removal of water from the top and base of the sample can induce non-uniform pressures as illustrated schematically in Figure 3-8. This problem is, fortunately, amenable to solution because membrane compliance-induced volume changes (and thus injection/removal volumes) are small in fine soils, and it is in these fine soils that non-uniform pore pressure fields equalize slowly. This problem was minimized by connecting the injection system in such a manner that injection/removal occurred simultaneously at both the top and base of the samples tested. The potential adverse impact of non-uniform internal sample pore pressure fields were then avoided by conservatively adopting the slow testing rates described in Chapter 4.

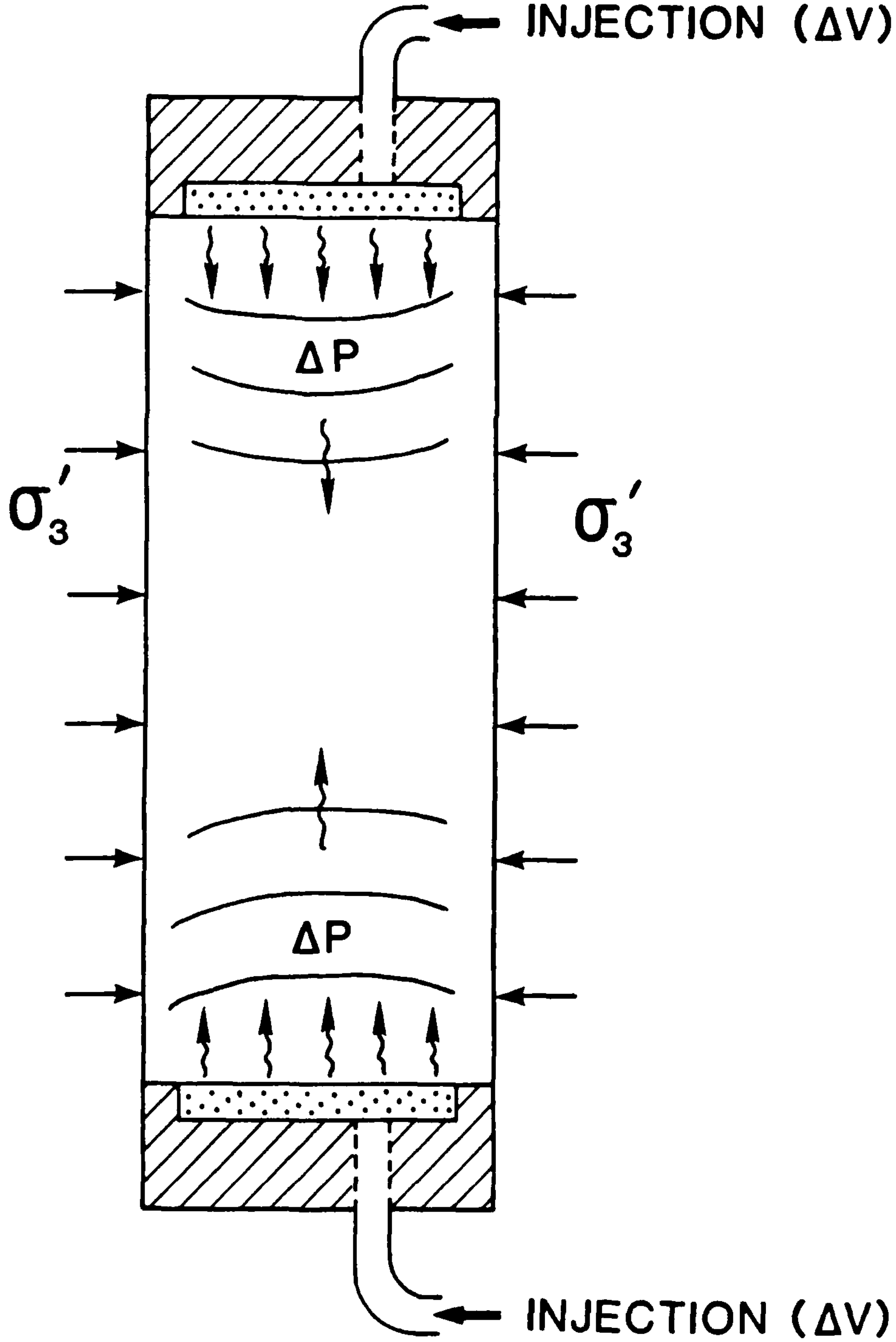


Figure 3-8: SCHEMATIC ILLUSTRATION OF INJECTION-INDUCED SAMPLE PORE PRESSURE SURGES

4.0 IMPLEMENTATION OF COMPUTER-CONTROLLED COMPLIANCE MITIGATION

4.1 General:

The membrane compliance mitigation methods and computer-controlled injection/removal system described in Chapter 3 were implemented in performing both undrained monotonic and undrained cyclic triaxial tests on samples 2.8 inches in diameter. Tests of both types were performed, with and without implementation of injection-mitigation, in order to provide a comparative basis for evaluation of the effectiveness of these membrane compliance mitigation procedures.

All tests were performed on Monterey 16 sand, a uniformly graded medium sand with a gradation distribution as shown in Figure 4-1. This is a clean, predominantly quartzitic beach sand, with subangular to subrounded particles. Monterey 16 sand was selected for this testing program for its ease of handling and its lack of unusual characteristics, because it is coarse enough that membrane compliance effects can significantly influence the results of undrained triaxial tests on 2.8-inch diameter samples, and beause it is fine enough that compliance effects would not be "expected" to exert an overwhelming influence on undrained test behavior.

Membrane compliance curves for Monterey 16 sand showing unit compliance (δV_m) as a function of effective confining stress for a range of densities were shown previously in Figure 3-5. This material has a maximum dry density of 110.8 pcf, as determined by the Modified Japanese Method in which the sample is placed dry in very small layers into a cylindrical mold and the mold is sharply hammered around its perimeter with a fixed number of blows per layer. The test is repeated several times, increasing the number of blows per layer, until these increases result in no further increase in $\gamma_{d,max}$. This procedure normally results in a slightly higher $\gamma_{d,max}$ for clean sands than do

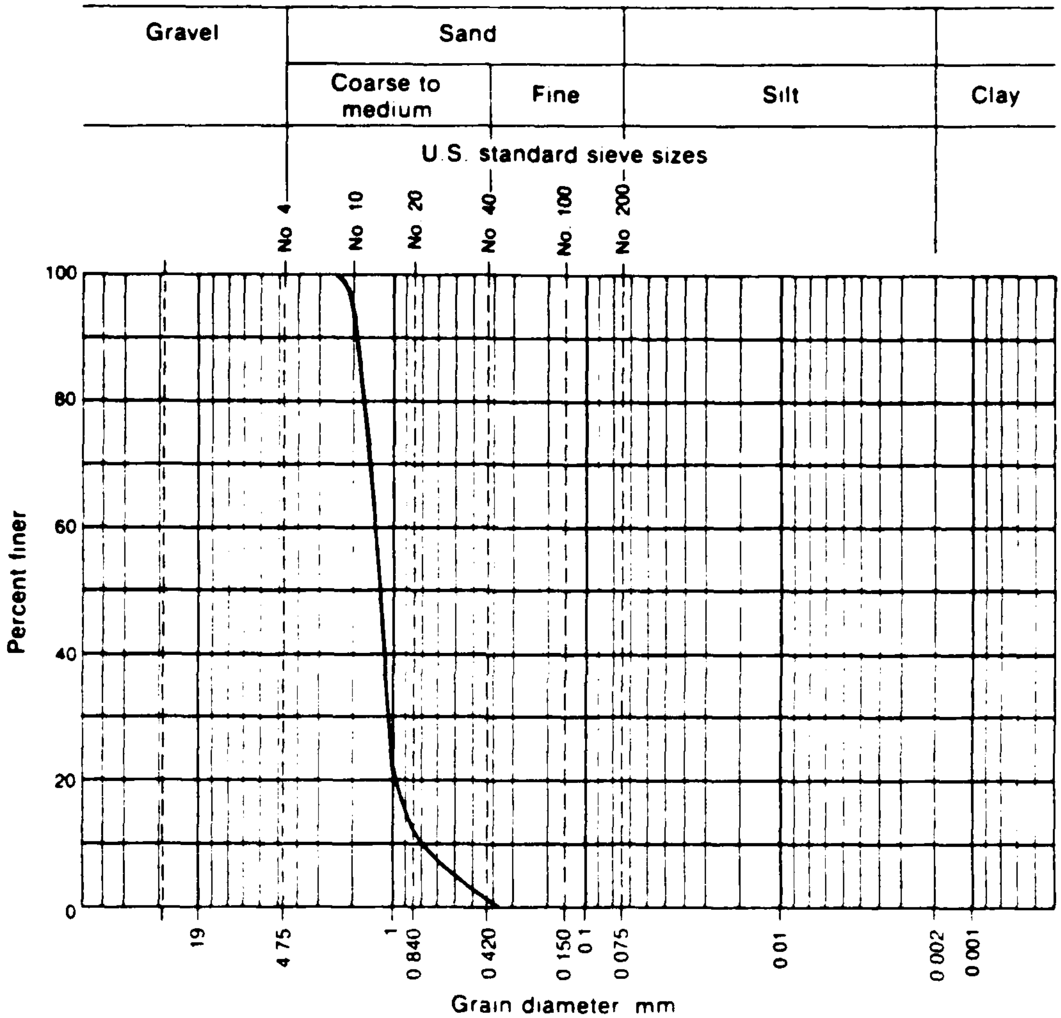


Figure 4-1: GRADATION CURVE FOR MONTEREY 16 SAND

recommended ASTM tests for $\gamma_{d,max}$. As a check, the Modified AASHTO Compaction Test (ASTM 1557D) resulted in a $\gamma_{d,max}$ of 109.9 pcf for this material, though this test result is not strictly valid as a basis for evaluation of relative density (D_R) due to grain breakage. The minimum dry density for this material is 97.0 pcf, as evaluated by pluviation through water. Monterey 16 sand has an average specific gravity of G_s = 2.65.

4.2 Undrained Monotonic Triaxial Testing:

A series of isotropically consolidated, undrained monotonic loading triaxial tests (IC-U Tests) were performed on five pairs of samples which were formed and consolidated to five different relative densities (D_R = 15%, 19%, 22%, 29%, and 40%) as listed in Table 4-1. At any given relative density, both samples in a pair were identically prepared and then one was tested "conventionally" (without injection-mitigation) and the other was tested with implementation of the computer-controlled injection-mitigation process.

Table 4-1: Testing Conditions: IC-U Triaxial Tests on Monterey 16 Sand With and Without Membrane Compliance Mitigation

Test No.	D_R (%)	Membrane Compliance Mitigation	Initial Confining Stress: $\sigma'_{3,c}$ (psi)	B-Value
1A	15	Yes	44.1	0.991
1B	15	No	44.1	0.993
2A	19	Yes	44.1	0.987
2B	19	No	44.1	0.990
3A	22	Yes	44.1	0.988
3B	22	No	44.1	0.989
4A	29	Yes	44.1	0.983
4B	29	No	44.1	0.990
5A	40	Yes	44.1	0.987
5B	40	No	44.1	0.981

All samples were formed by moist tamping, all were saturated by a vacuum/ back-pressure saturation procedure similar to that described by Rad and Clough (1984), and all were isotropically consolidated to an initial effective confining stress of 44.1 psi. In order to ensure that incomplete sample saturation would not contribute to overall compliance, all samples were back-pressure saturated to a minimum B-value greater than or equal to 0.98. All tests were strain-controlled, with an axial strain rate of 0.5% per minute in order to ensure a uniform internal sample pore pressure distribution in tests with and without injection mitigation.

The results of these undrained tests on pairs of samples at each of the five densities tested are shown in Figures 4-2 through 4-6. The three loosest pairs of samples were all contractive under these testing conditions, while the two denser pairs of samples were initially contractive (developed positive pore pressure) at small strains but dilated at larger strains. The densest pair of samples reached a state of pore water cavitation before achieving critical-state confining stress conditions.

In all five pairs of tests the initial rate of pore pressure generation (at small strains) was greater in samples with injection-mitigation than in samples without mitigation of membrane compliance. In the three "loose" pairs of samples, tests with compliance mitigation resulted in higher final, residual pore pressure (lower critical-state confining effective confining stresses) than tests without mitigation. In the two "dense" pairs of tests, mitigation of membrane compliance effects produced higher positive pore pressures at small strains and higher negative (dilatent) pore pressures at large strains than tests without mitigation. These behavior patterns suggest, but by no means prove conclusively, that the computer-controlled injection/removal process successfully mitigates the potentially adverse effects of membrane compliance.

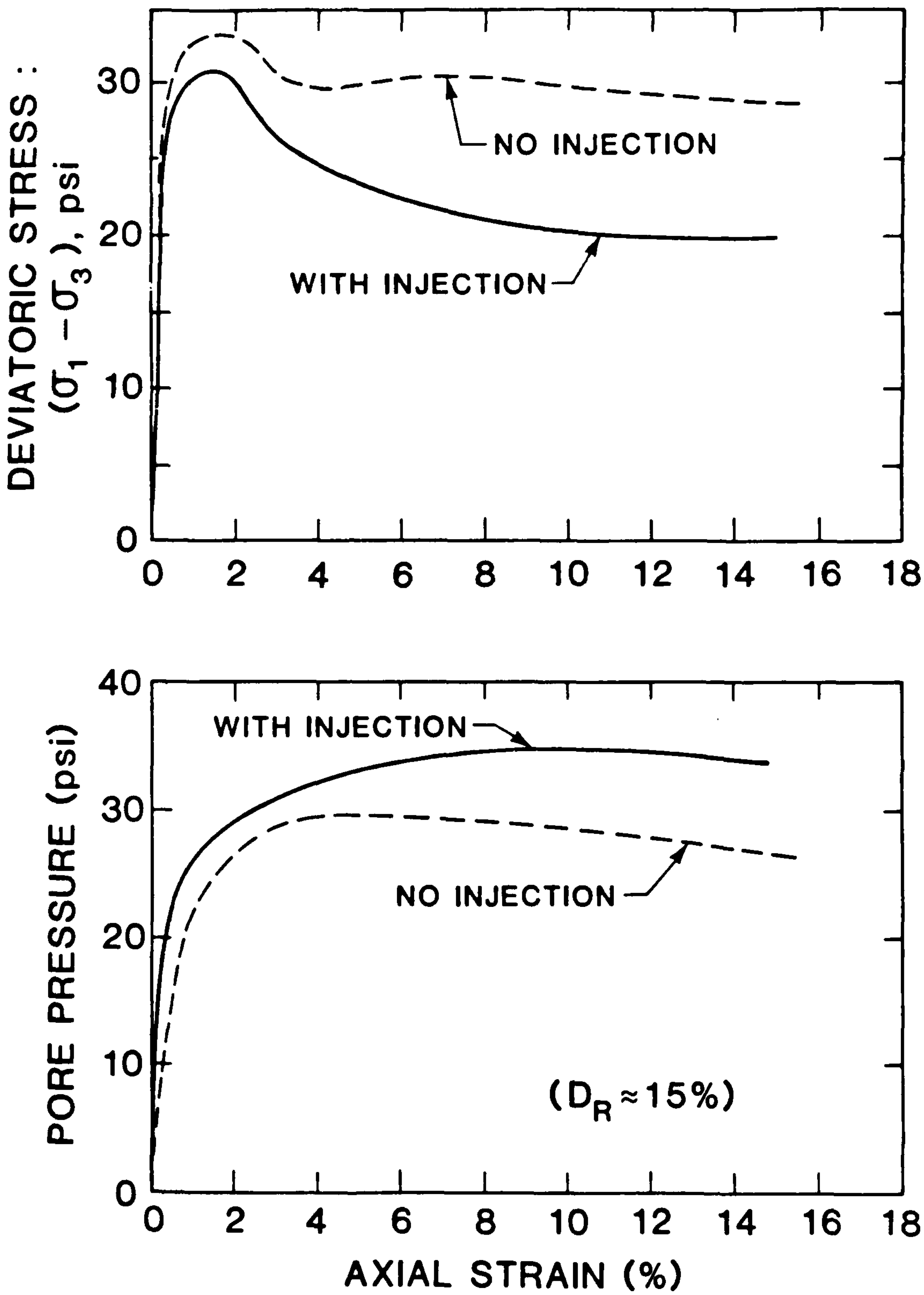


Figure 4-2: IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION ($D_R \approx 15\%$)

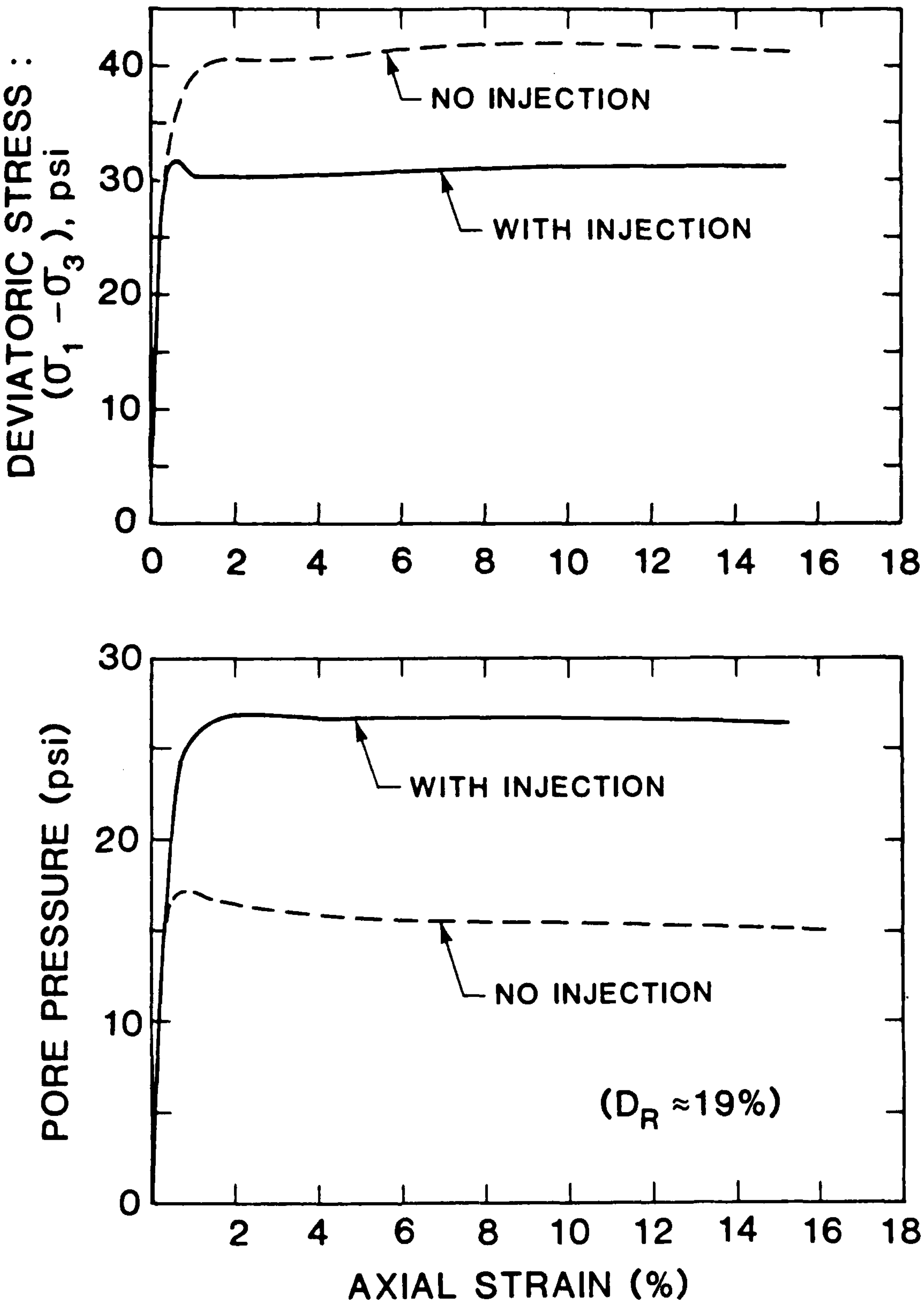


Figure 4-3: IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION ($D_R \approx 19\%$)

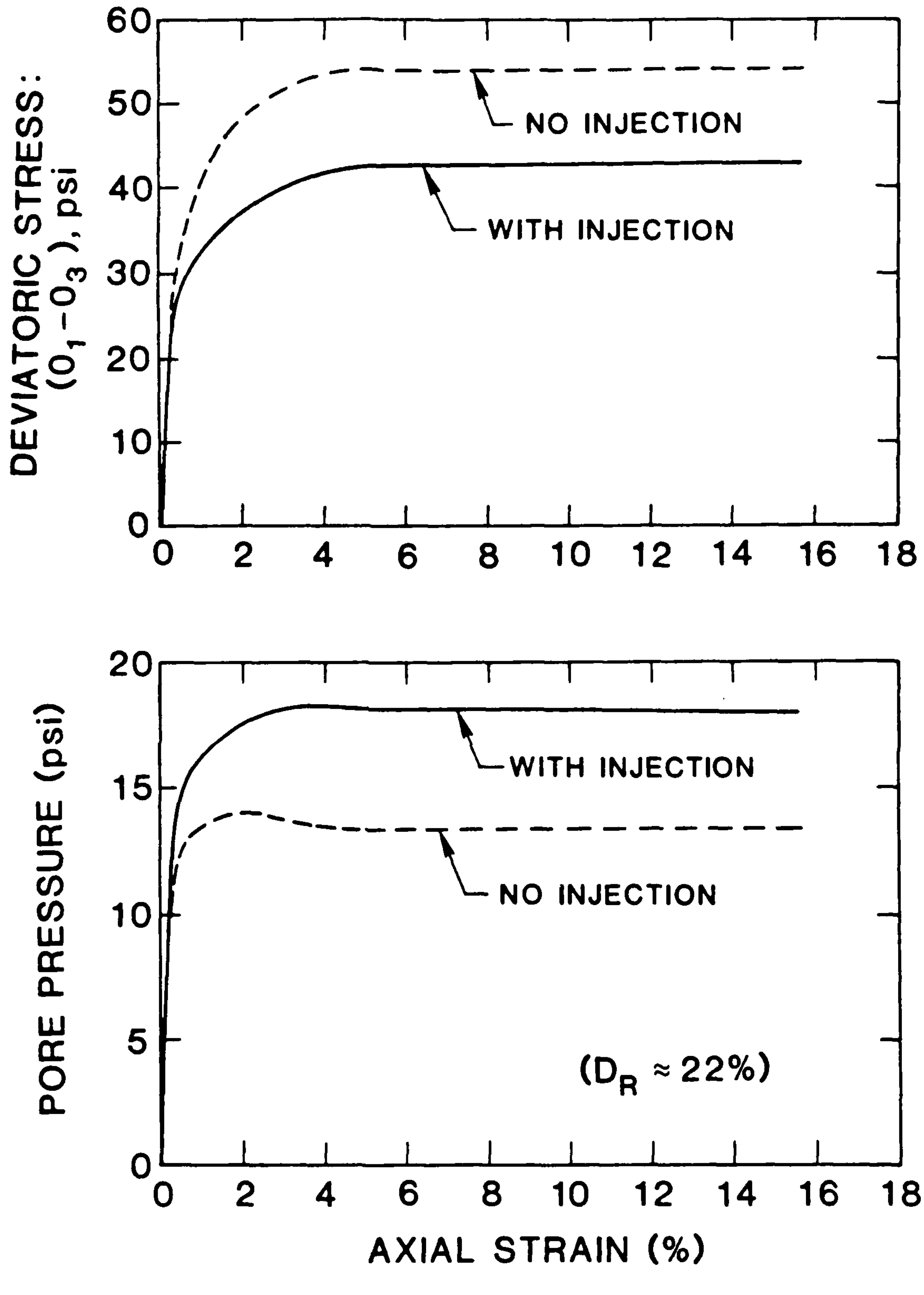


Figure 4-4: IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION ($D_R \approx 22\%$)

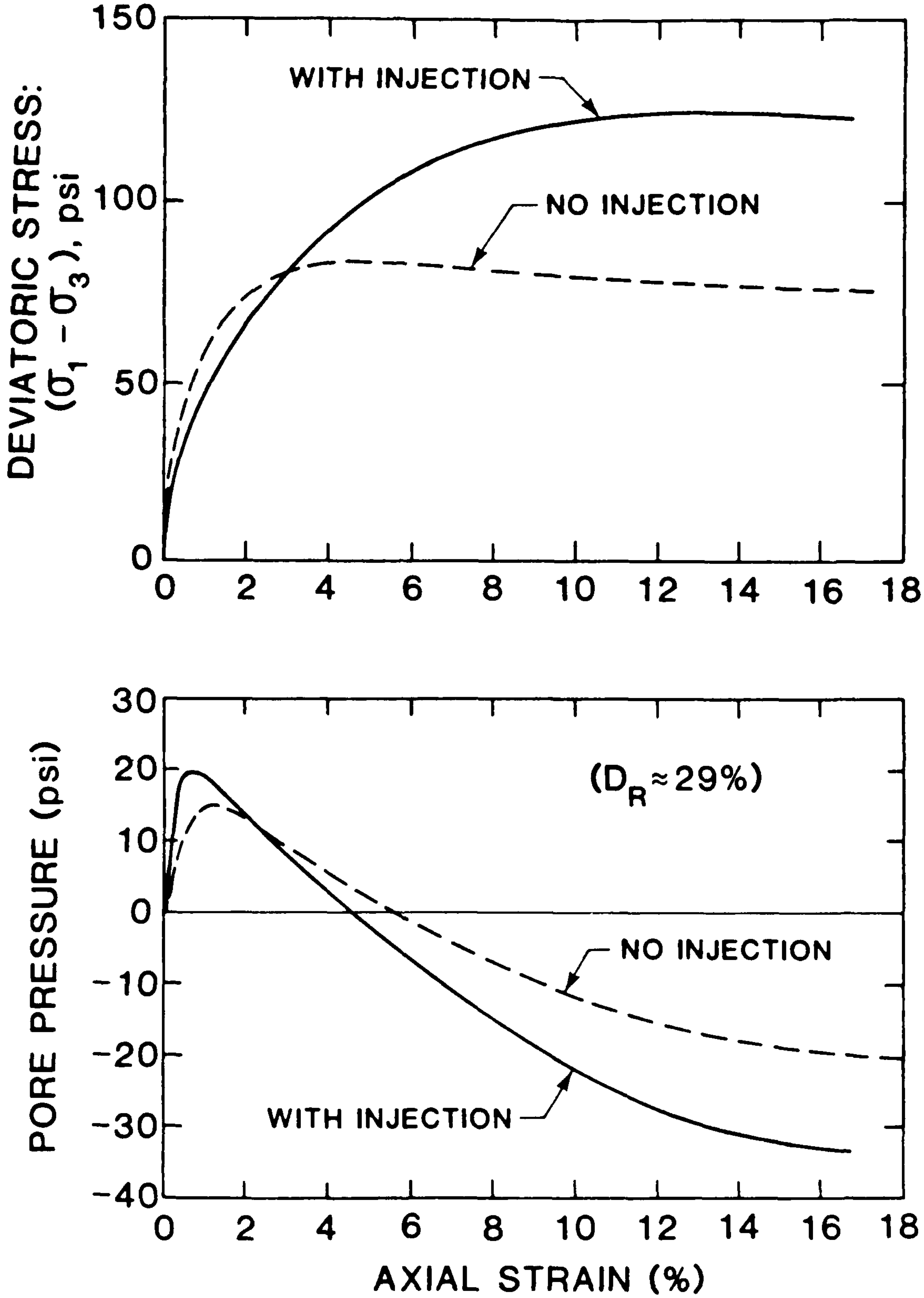


Figure 4-5: IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION ($D_R \approx 29\%$)

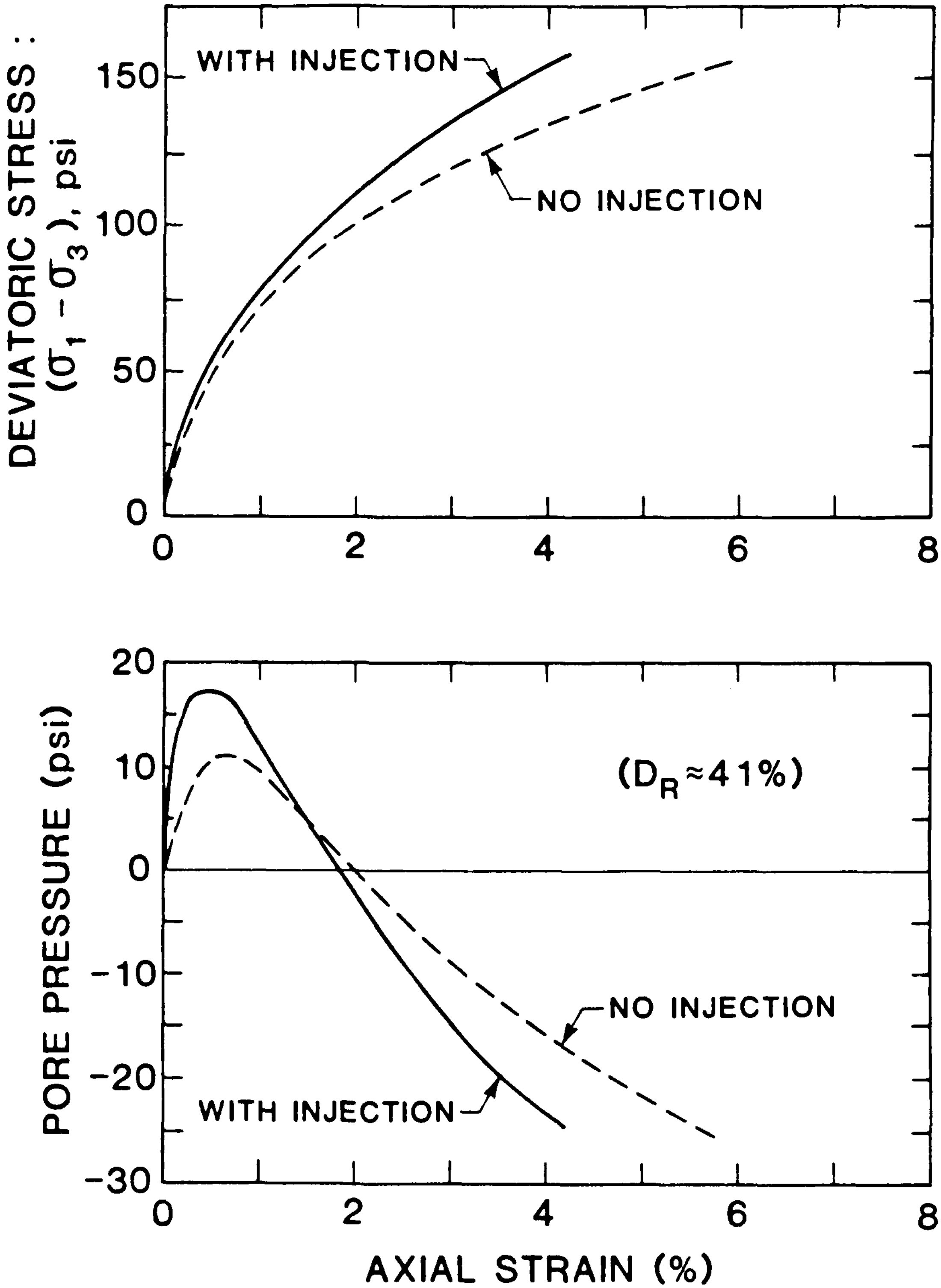


Figure 4-6: IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION ($D_R \approx 40\%$)

Further insight into the effectiveness of this membrane compliance mitigation methodology can be gained by examining these test results using "critical-state" principles of soil mechanics. Figure 4-7 shows a plot of residual (critical-state) effective confining stress as a function of void ratio for the five IC-U tests with compliance mitigation. The solid line in this figure represents the "critical-state line" for Monterey 16 sand as determined by these tests.

Figure 4-8 again shows the critical-state line based on "truly undrained conditions" (tests with injection-mitigation). Also shown in this figure are the residual or critical-state conditions as determined by the conventional IC-U tests (tests without mitigation of membrane compliance). As shown in this figure, these conventional tests would suggest a very different critical-state line, if assumed to be "undrained" as is conventionally done, than would the tests with mitigation. This is, of course, due to the underestimation of both positive and negative pore pressure changes in the conventional tests as a result of membrane compliance.

Because of membrane compliance, the "conventional" tests are not truly undrained, but instead experience volume changes (changes in membrane penetration) due to the changes in effective confining stress which occur during testing. The final (critical-state) sample density or void ratio accounting for these membrane compliance-induced volume changes can be calculated by determining the final change in unit membrane compliance (δV_m) from Figure 3-5 based on the final change in effective confining stress. This represents a good opportunity to evaluate the effectiveness of the computer-controlled injection/removal procedure.

If the results of the "conventional" tests are correctly interpreted as partially drained tests (with associated volume changes), and volume changes

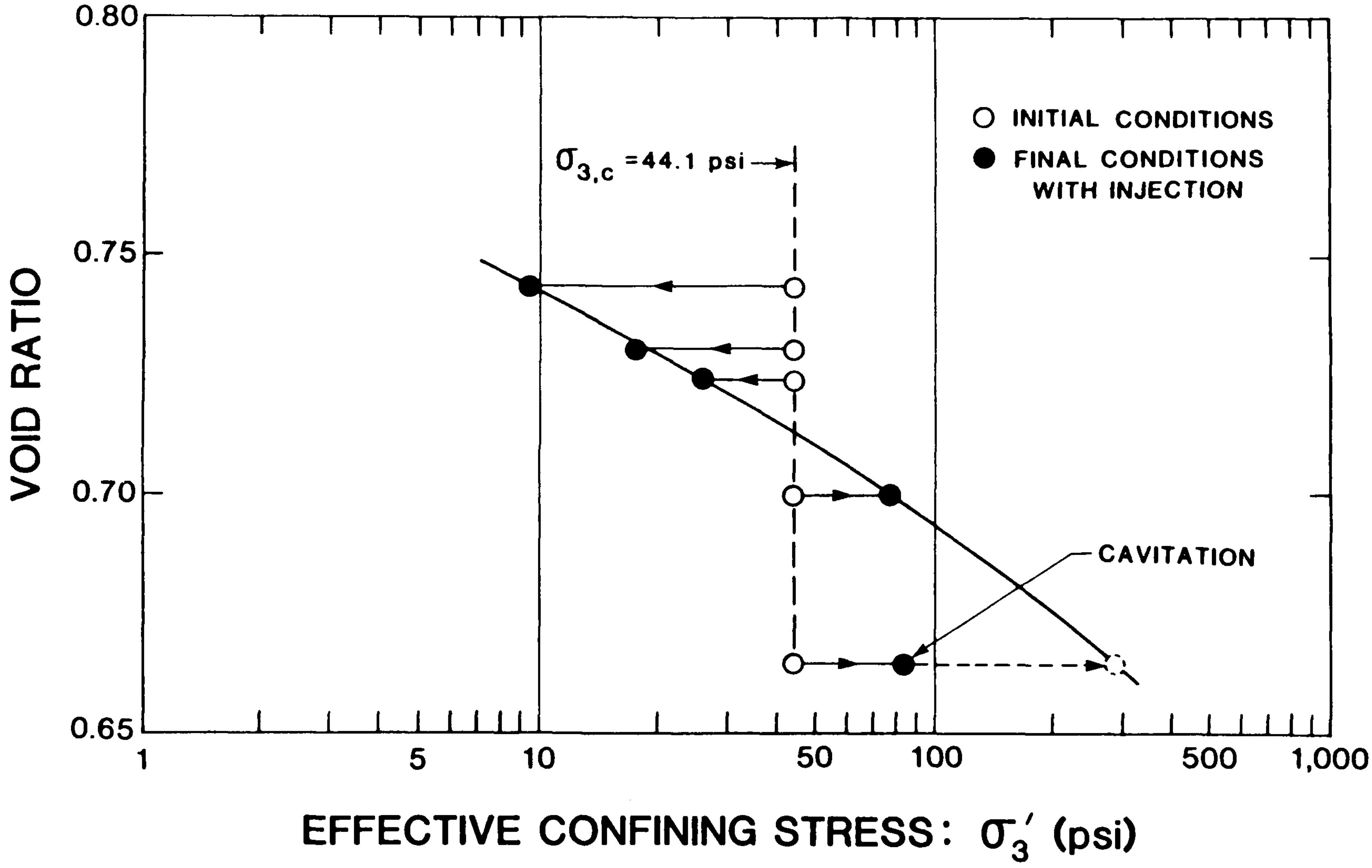


Figure 4-7: CRITICAL-STATE PLOT FOR IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH IMPLEMENTATION ON INJECTION-MITIGATION

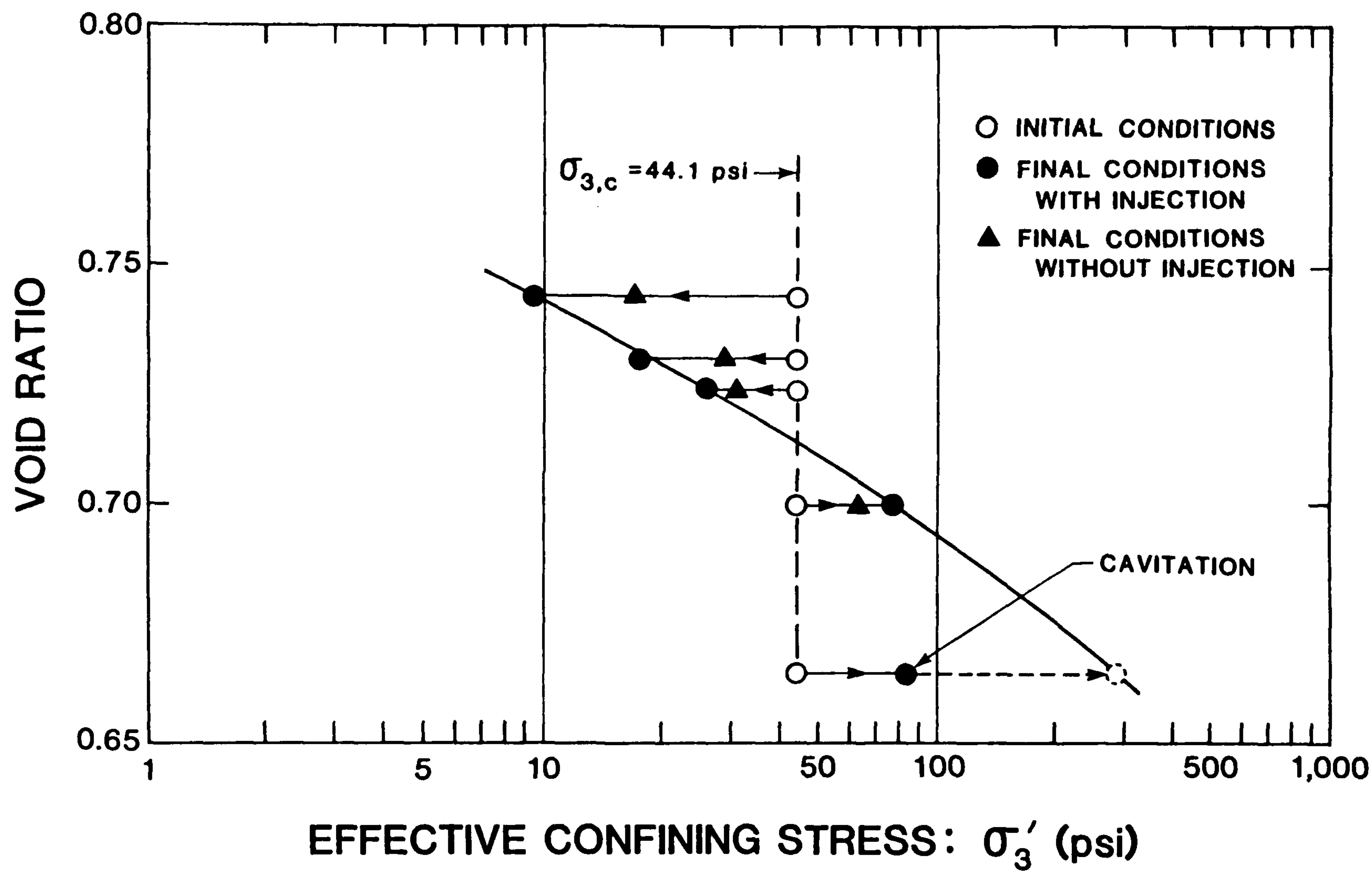


Figure 4-8: CRITICAL-STATE PLOT FOR IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION (WITH NO CORRECTION FOR MEMBRANE COMPLIANCE-INDUCED VOLUMETRIC CHANGES)

are based on Figure 3-5, then the crilical-state conditions for these conventional tests can be re-plotted as shown in Figure 4-9. As shown in this figure, the conventional test results plot on or very near the "corrected" critical-state line as determined by the tests with computer-controlled injection/removal compliance mitigation, providing good support for the accuracy and effectiveness of this method for mitigation of the effects of membrane compliance during undrained testing.

4.3 Undrained Cyclic Triaxial Testing:

Isotropically consolidated undrained cyclic triaxial tests were performed on 2.8-inch diameter samples of Monterey 16 sand in order to investigate the influence of membrane compliance on undrained cyclic tests. Two series of tests were performed: one with implementation of injection-mitigation and one "conventional" series of tests without mitigation of membrane compliance effects.

Samples were formed and saturated using the same procedures as were described in Section 4.2. All samples were isotropically consolidated to an initial effective confining stress of 29.4 psi with relative densities of approximately D_R = 55%. Table 4-2 lists the initial test conditions for these cyclic tests. Three pairs of tests were performed at cyclic stress ratios of approximately 0.20, 0.25 and 0.30, where cyclic stress ratio is defined as

$$CSR = \frac{\sigma_{d,c}}{2\sigma'_{3,i}}$$

Tests were performed with sinusoidal cyclic loading at a rate of one cycle per 10 seconds (0.1 Hz). This slow testing rate was adopted to promote a uniform internal sample pore pressure distribution within the samples subjected to computer-controlled injection/removal during testing. In order to investigate the possibility that this slow rate of cyclic loading might

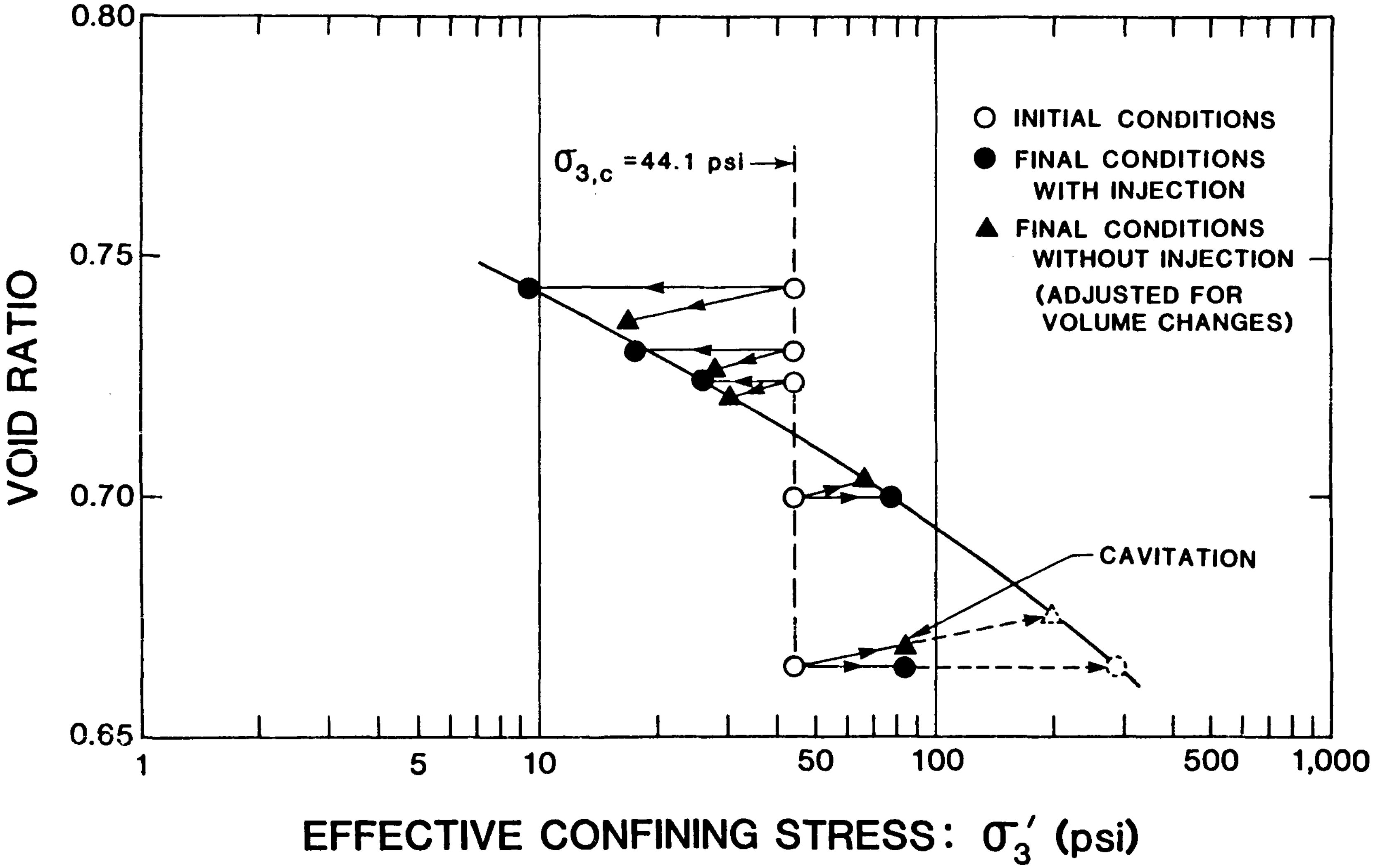


Figure 4-9: CRITICAL-STATE PLOT FOR IC-U TRIAXIAL TESTS ON MONTEREY 16 SAND WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION (WITH CORRECTION FOR MEMBRANE COMPLIANCE-INDUCED VOLUME CHANGES)

Table 4-2: Isotropically Consolidated Undrained Cyclic Triaxial Tests on Monterey 16 Sand With anbd Without Membrane Compliance Mitigation

Test No.	D_R (%)	Membrane Compliance Mitigation	Initial Confining Stress: $\sigma'_{3,i}$ (psi)	B-Value	CSR ($\sigma_{d,c}/2\sigma'_a$)	No. of Cycles to ± 5% ε_A
1A	55.5	Yes	29.4	0.993	0.203	4
2A	55.7	Yes	29.4	0.987	0.248	7
3A	54.8	Yes	29.4	0.993	0.299	79
1B	55.0	No	29.4	0.992	0.205	7
2B	56.0	No	29.4	0.996	0.255	26
3B	55.8	No	29.4	0.988	0.303	See Note

Note: Test No. 3B was stopped at 400 cycles with pore pressure ratio $r_u \approx 0.6$.

adversely influence the test results, two additional series of undrained cyclic triaxial tests had previously been performed on 2.8-inch diameter samples of Monterey 60 sand. Monterey 60 sand is a fine, uniformly graded beach sand from the same source as the Monterey 16 sand, and has similar grain characteristics and gradation distribution, but finer grains as shown in Figure 4-10.

Monterey 60 samples were isotropically consolidated to $\sigma'_{3,i}$ = 29.4 psi at a relative density of $D_R \approx 50\%$, and were then cyclically loaded at a cyclic load rate of either 0.1 Hz or 1.0 Hz. Figure 4-11 shows the results of these tests. This figure presents a plot of cyclic stress ratio (CSR) vs. number of cycles to "failure", where failure is defined as double amplitude cyclic strain of ± 5%. As shown in this figure, cyclic loading rate had no discernible influence on the test results.

Figures 4-12 through 4-17 show the results of the two series of cyclic triaxial tests (with and without membrane compliance mitigation) performed on samples of Monterey 16 sand. These test results are summarized in Figure 4-18 which shows the resulting cyclic strength curves for samples tested with compliance mitigation (solid line) and without mitigation (dashed line). As shown in these figures, the mitigation of membrane compliance effects significantly increased the rate of cyclic pore pressure generation and reduced the measured liquefaction resistance of this uniformly graded medium sand.

The "correct" cyclic strength curve (<u>with</u> compliance mitigation) shown in Figure 4-18 for Monterey 16 sand agrees well with the cyclic strength curve for Monterey 60 sand in Figure 4-11. This is to be expected, as both sands are mineralogically similar, have similar grain shapes and similar gradation distribution, and both were tested at similar relative densities ($D_R \approx 55\%$ and 50%, respectively). In fact, the Monterey 16 sand had a slightly higher relative density and exhibited a slightly higher resistance to liquefaction.

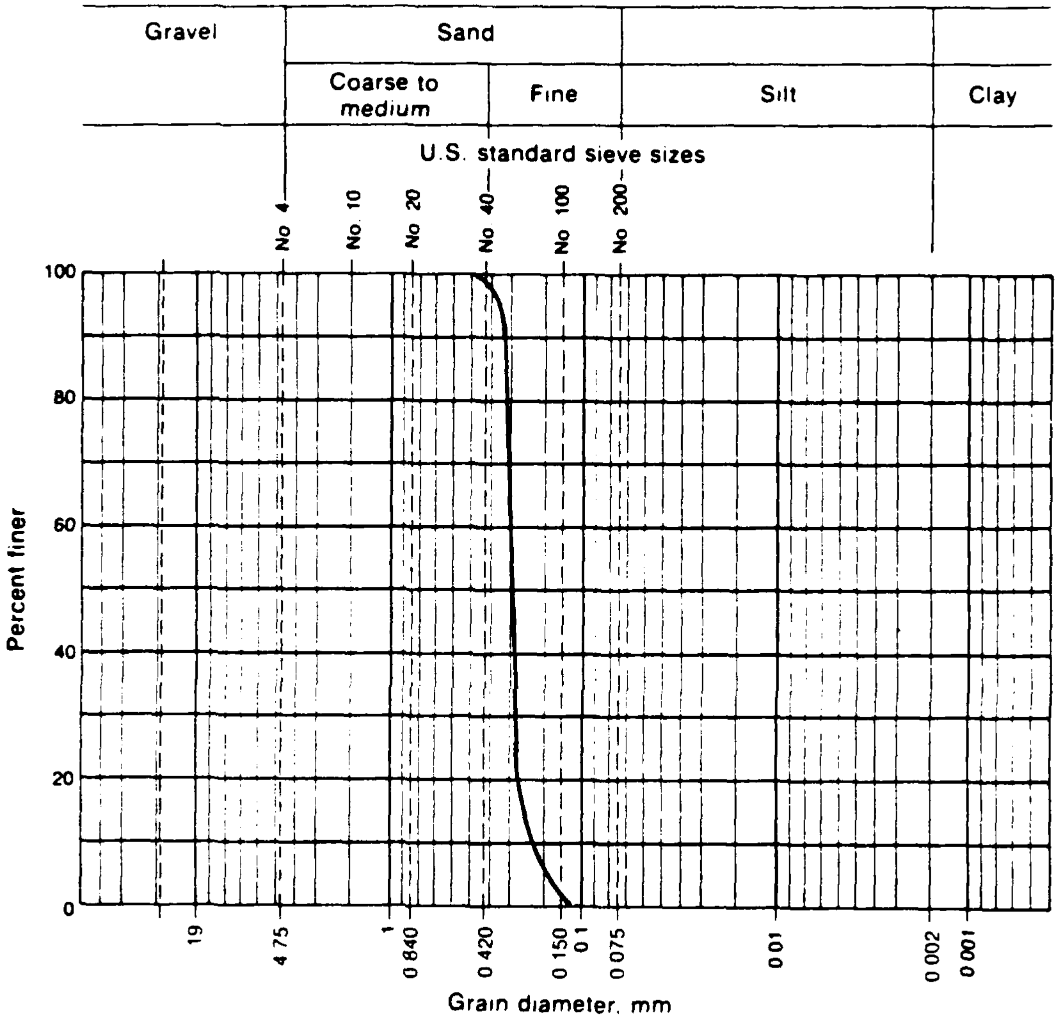


Figure 4-10: GRADATION CURVE FOR MONTEREY 60 SAND

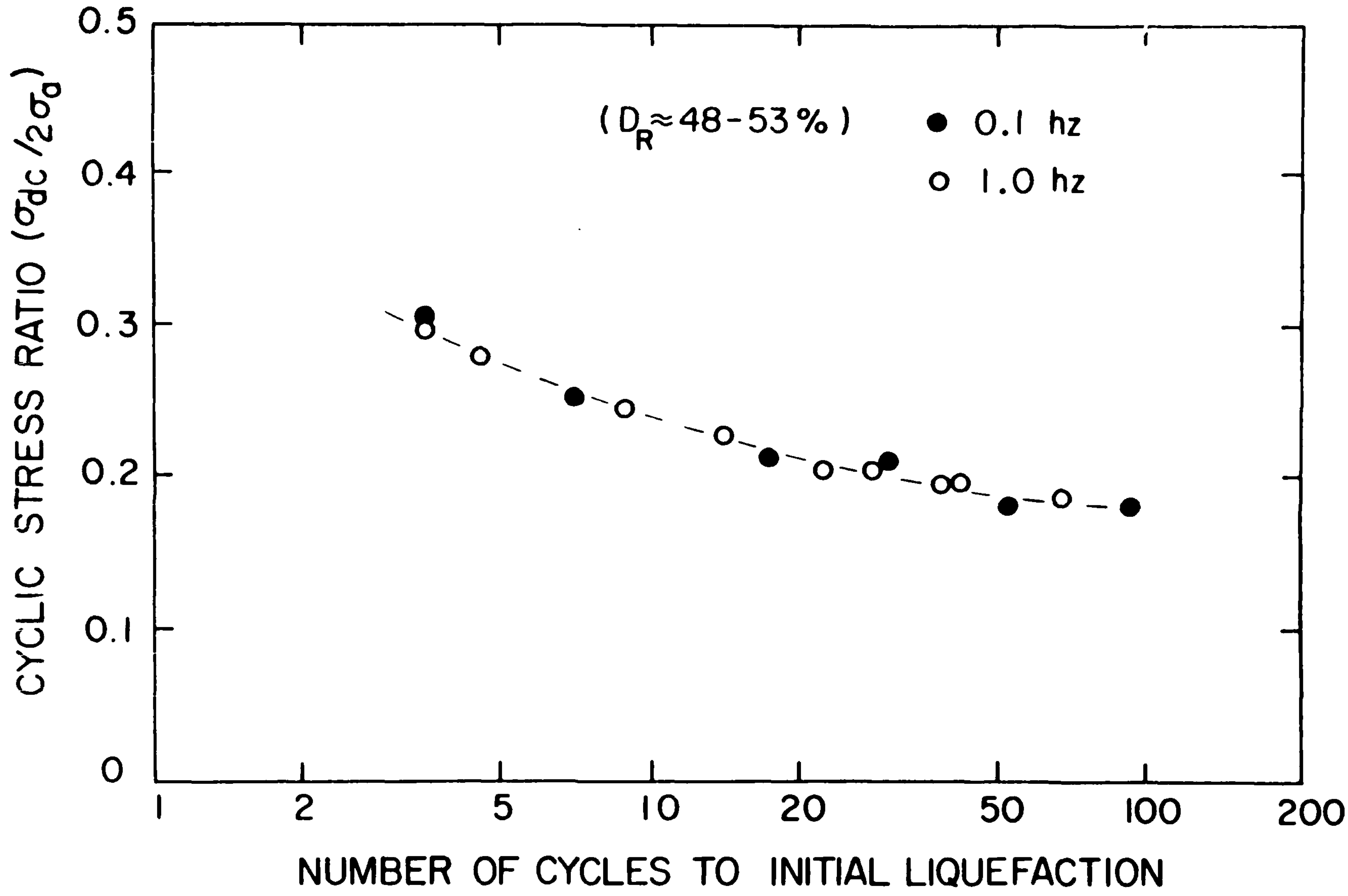


Figure 4-11: ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TESTS ON MONTEREY 60 SAND ($D_R \approx$ 50%) AT CYCLIC LOADING RATES OF 0.1 Hz AND 1.0 Hz

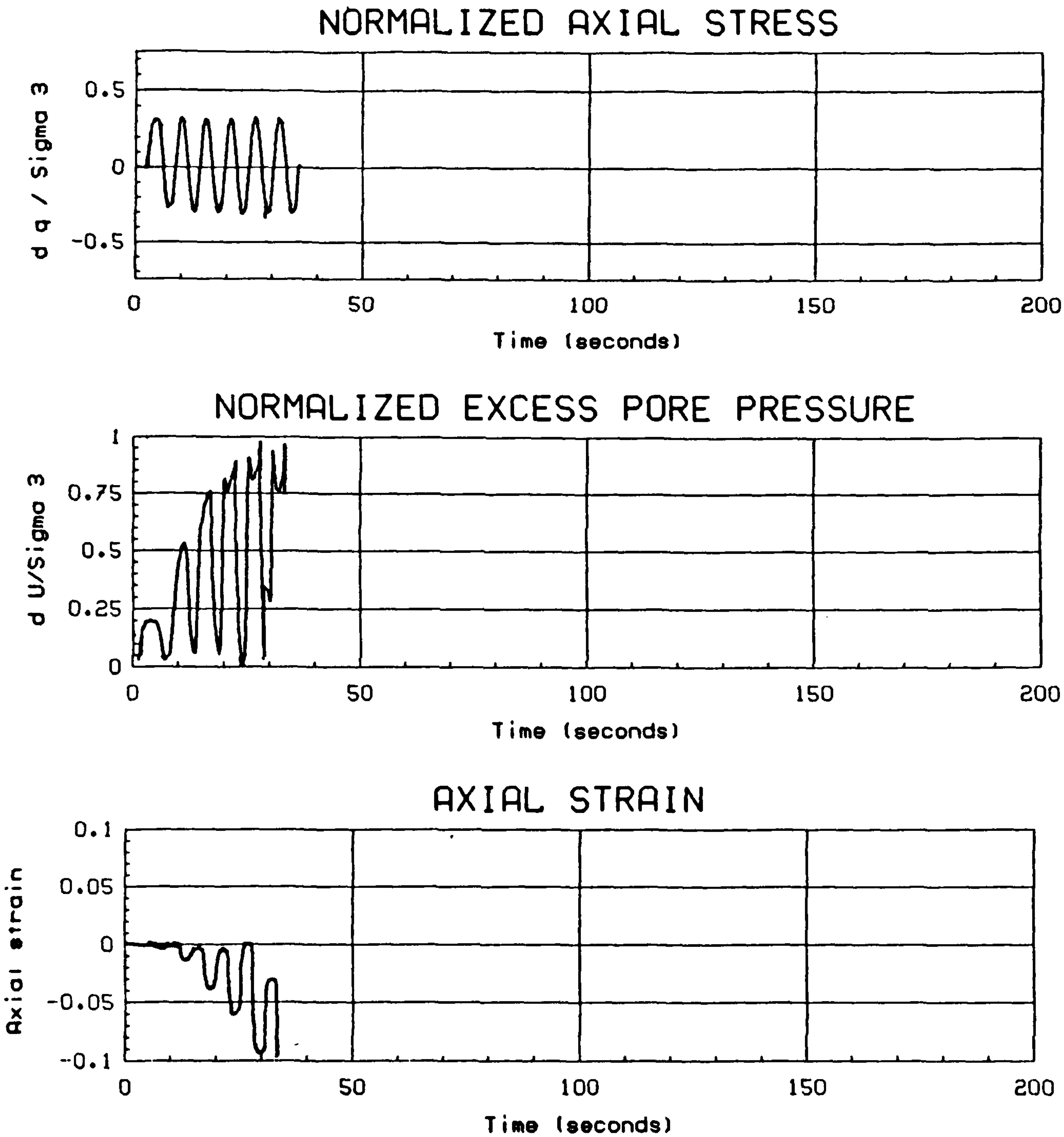


Figure 4-12: ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TEST NO. 1A

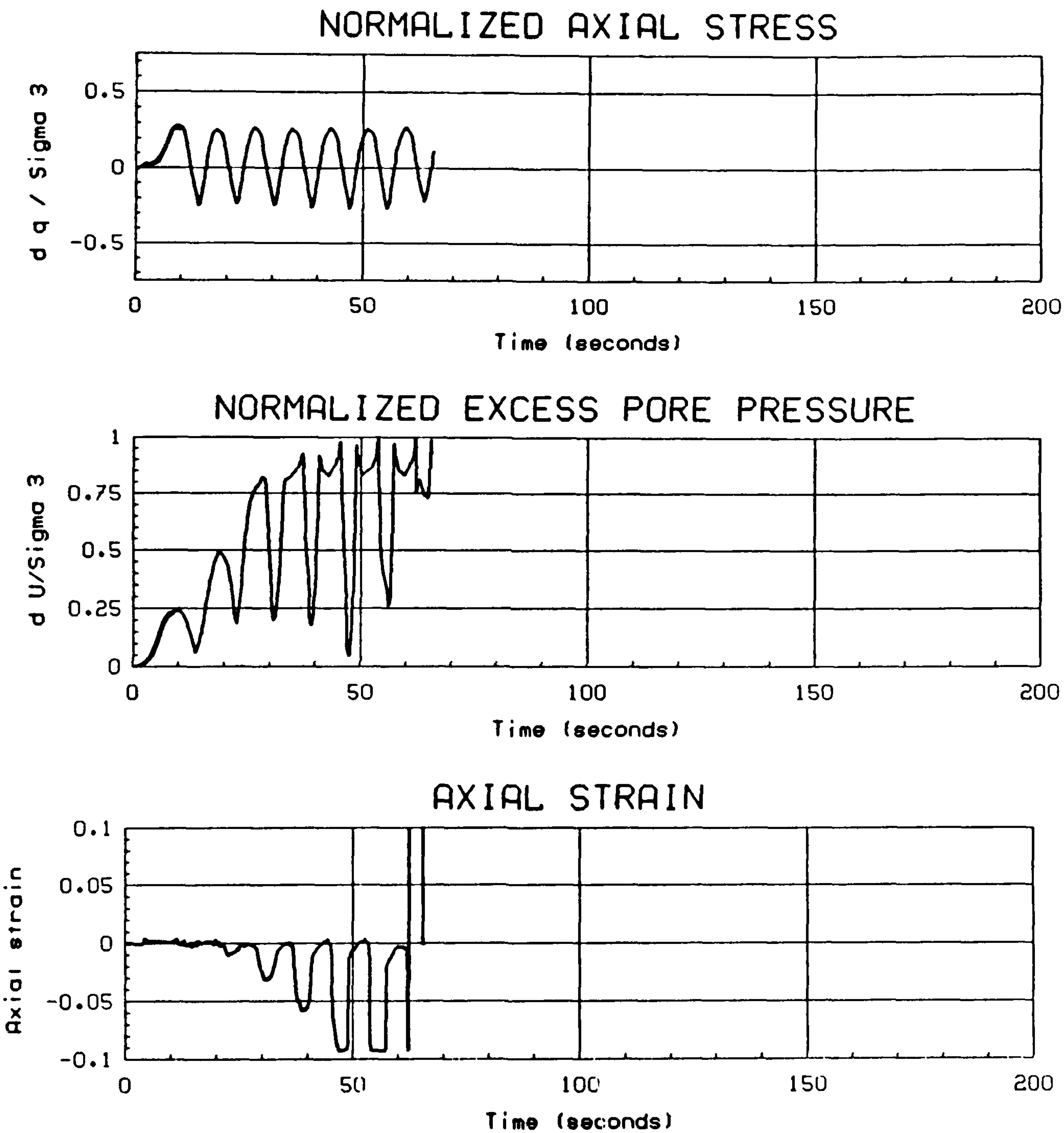


Figure 4-13: <u>ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TEST NO. 2A</u>

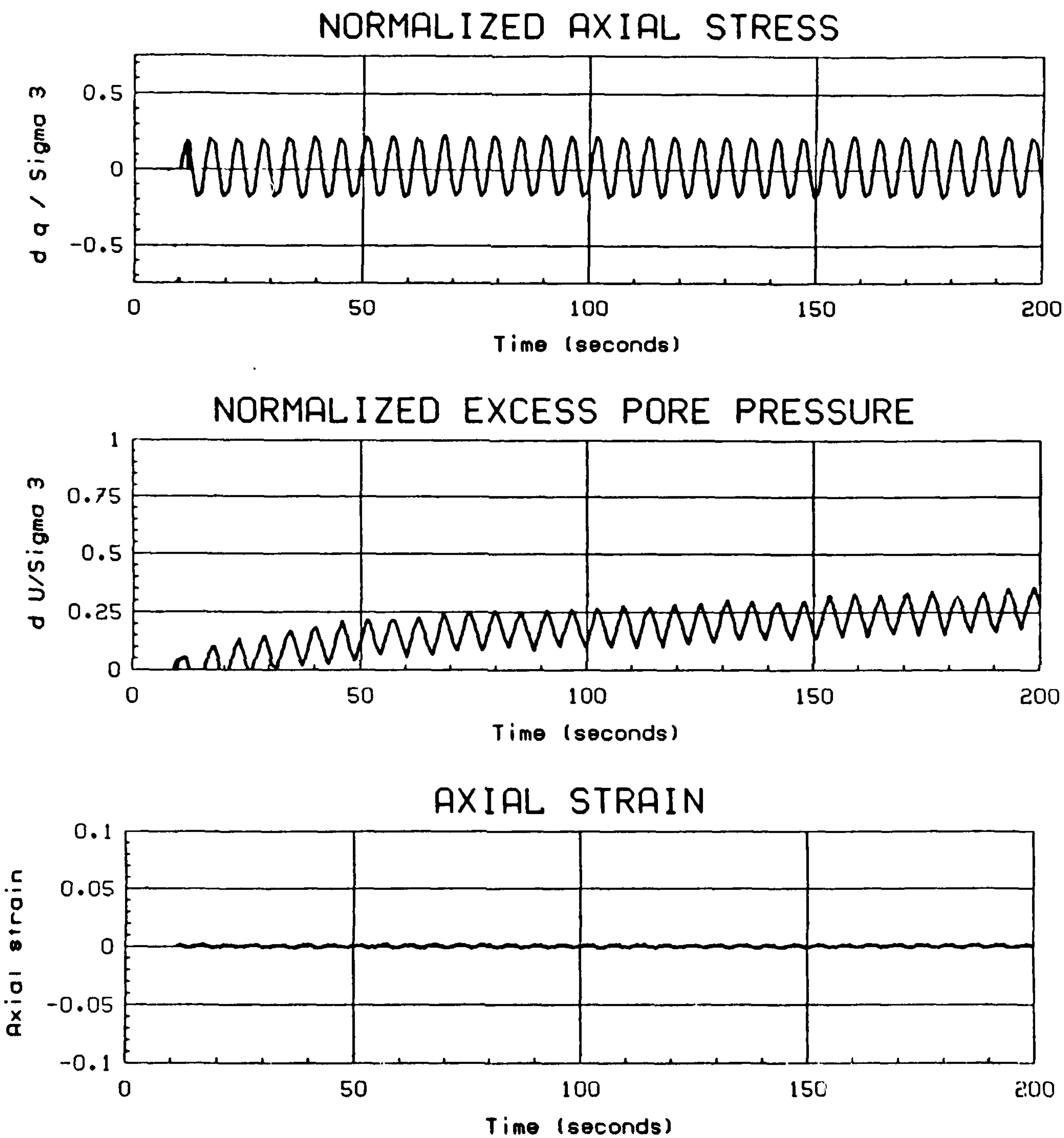


Figure 4-14: ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TEST NO. 3A

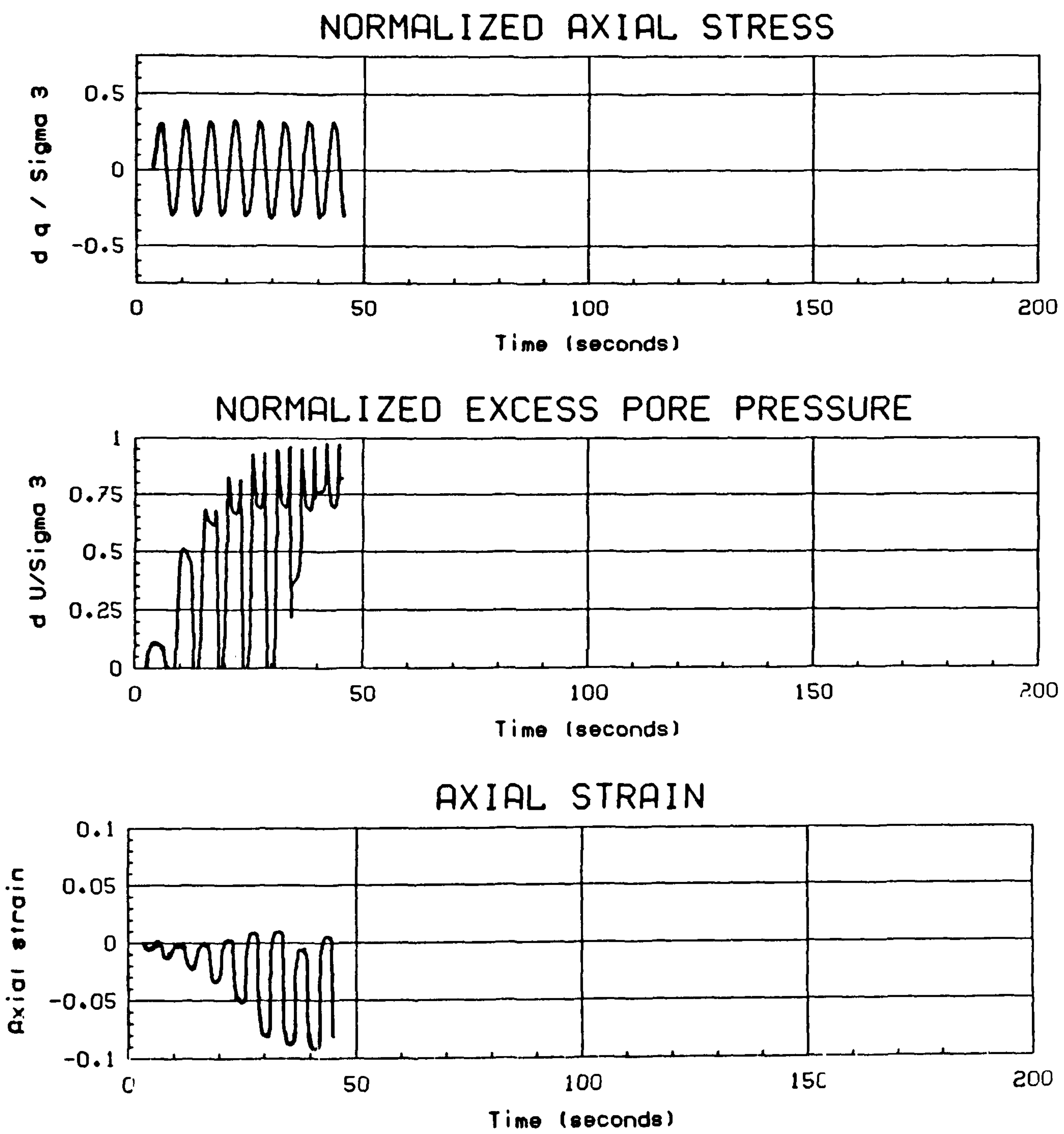


Figure 4-15: ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TEST NO. 1B

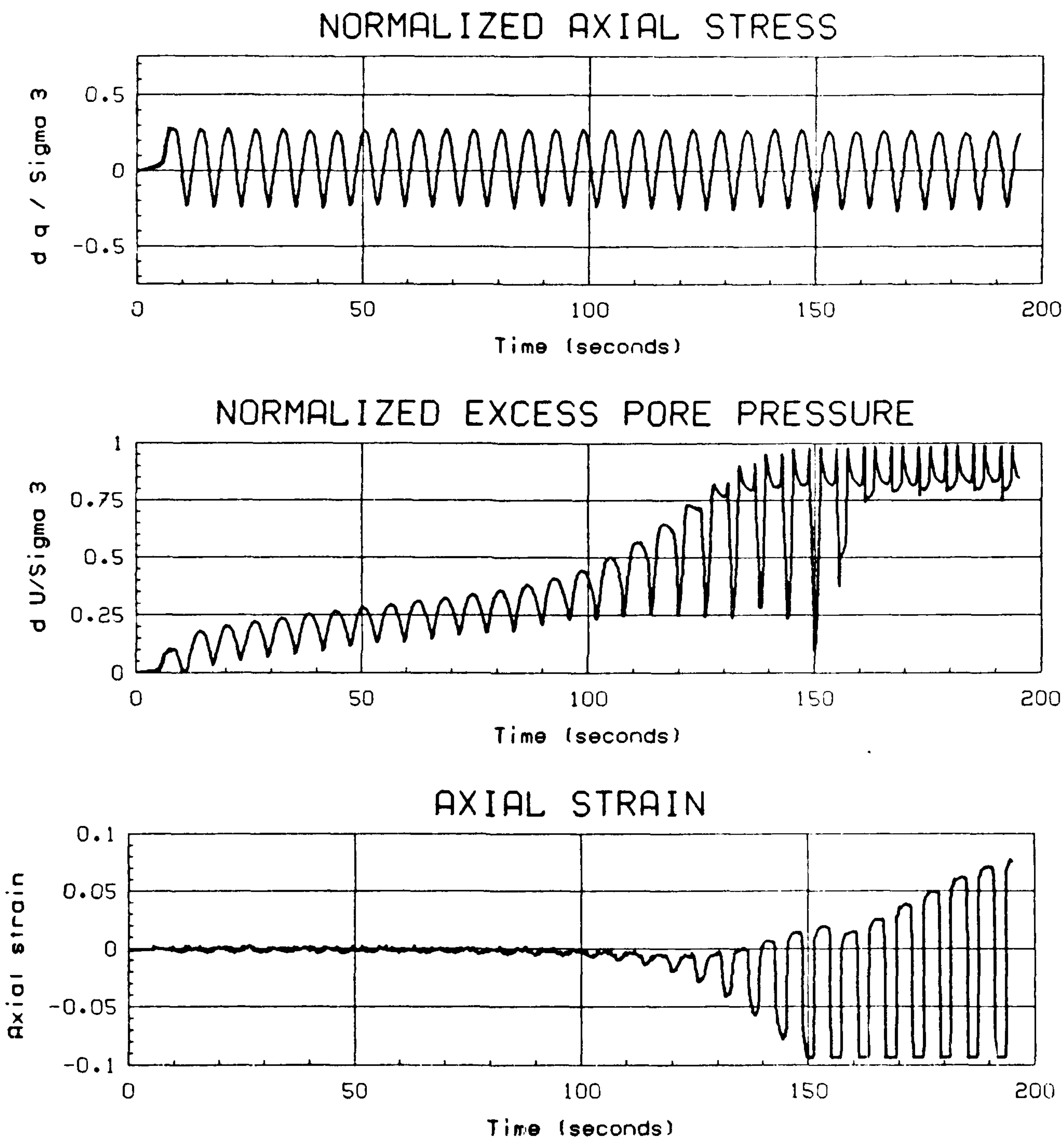


Figure 4-16: ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TEST NO. 2B

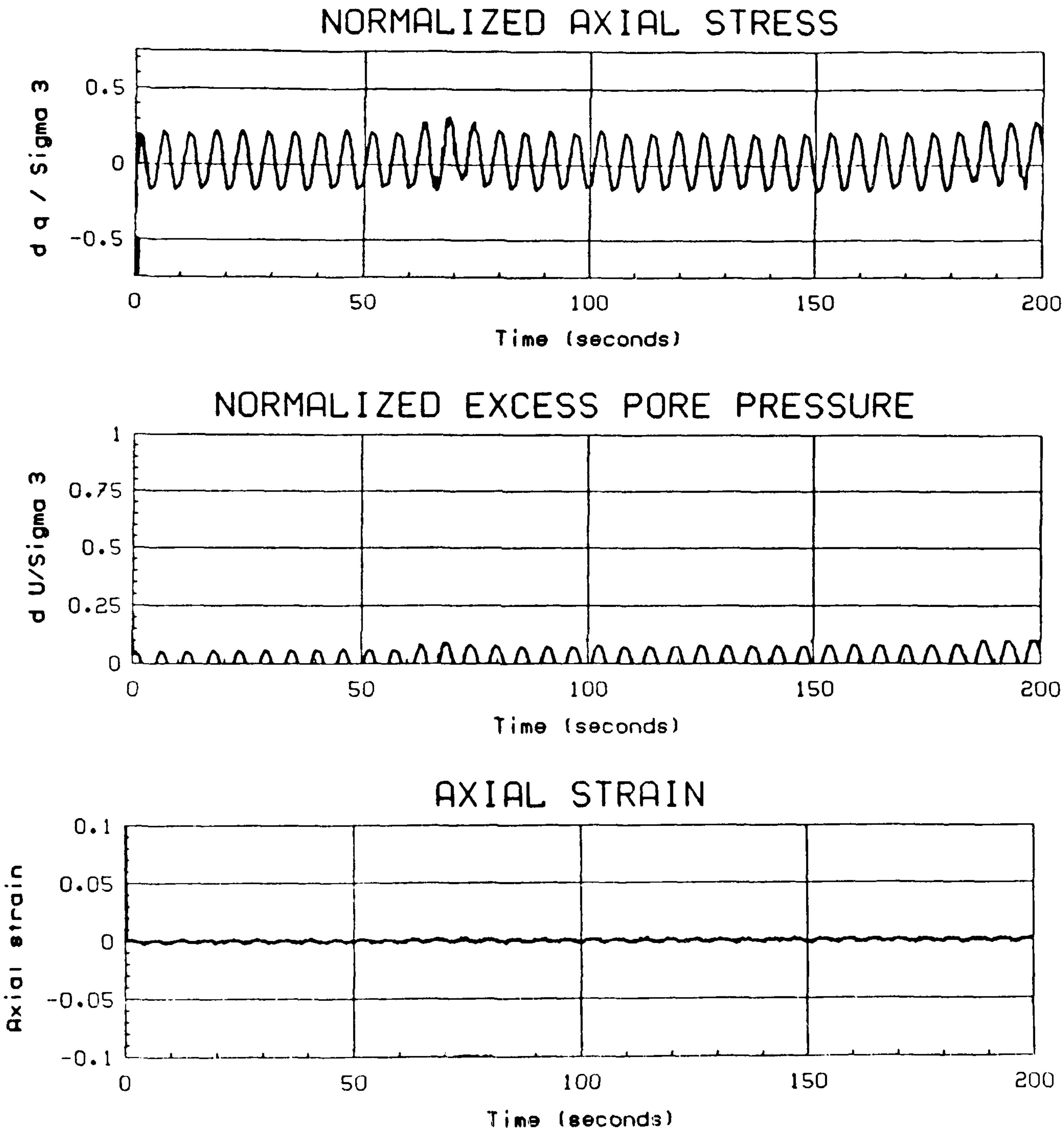


Figure 4-17: ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TEST NO. 3B

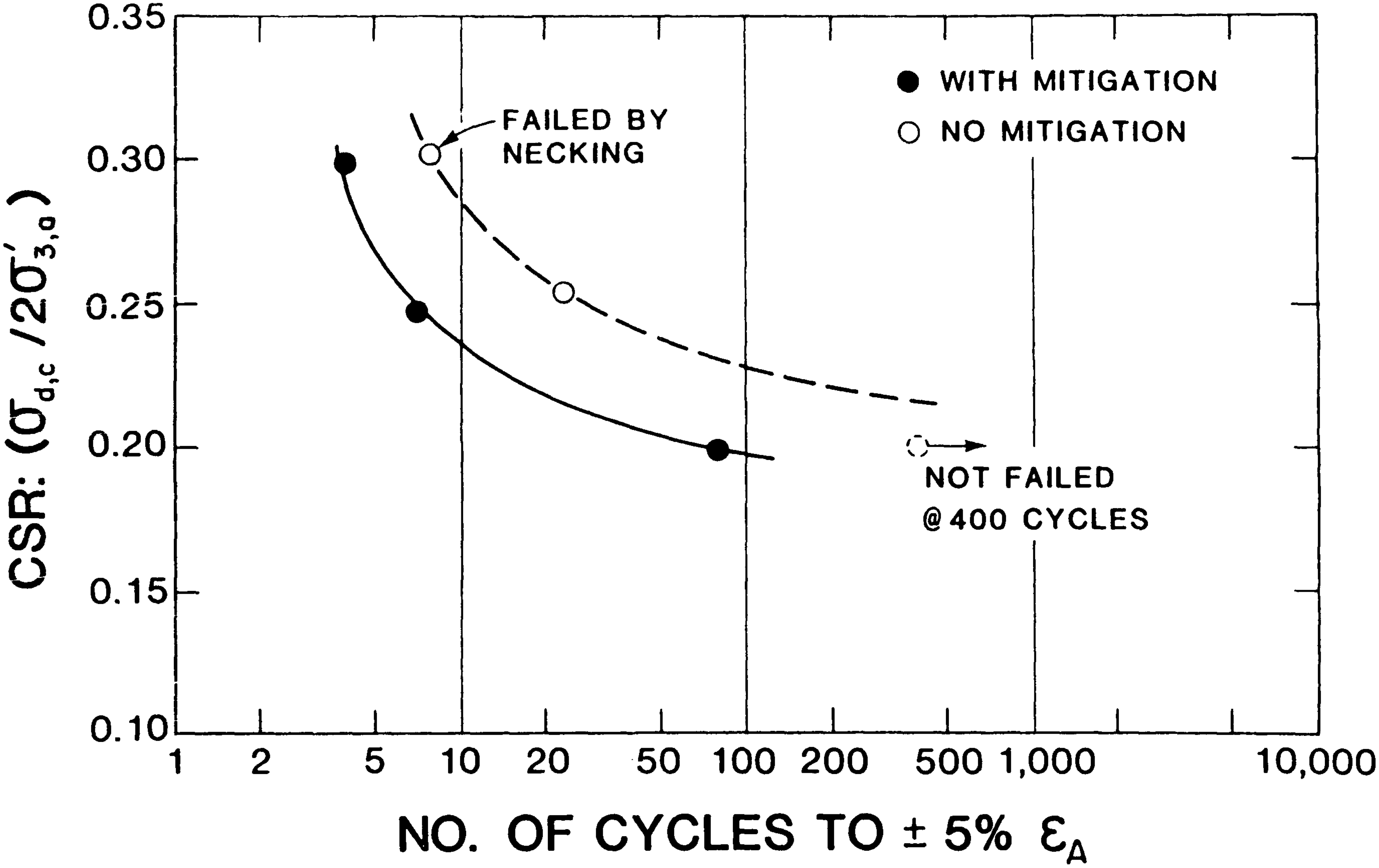


Figure 4-18: ISOTROPICALLY CONSOLIDATED UNDRAINED CYCLIC TRIAXIAL TESTS ON MONTEREY 16 SAND ($D_r \approx 55\%$) WITH AND WITHOUT MEMBRANE COMPLIANCE MITIGATION

The cyclic strength curve for "conventional" tests (without membrane compliance mitigation) represented by the dashed line in Figure 4-18, on the other hand, agrees very poorly with the cyclic strength curve shown in Figure 4-11. These conventional test results appear to significantly overestimate resistance to liquefaction because of the adverse influence of membrane compliance. This overestimation of cyclic strength represents approximately a factor of 20% increase in CSR for "failure" in any given number of cycles in samples tested without mitigation of membrane compliance effects.

These undrained cyclic triaxial tests again provide good support for the effectiveness and accuracy of the computer-controlled injection/removal procedures implemented for mitigation of the effects of membrane compliance. In addition, they represent the first undrained cyclic test series upon which to base quantitative judgements of the influence of membrane compliance on this type of testing, and the results suggest that these effects can be significant for 2.8-inch diameter triaxial samples of medium sands.

AD-A185 542 DEVELOPMENT OF A LABORATORY TECHNIQUE FOR CORRECTING 2/2
RESULTS OF UNDRAINED (U) STANFORD UNIV CALIF DEPT OF
CIVIL ENGINEERING R B SEED ET AL. SEP 87 SU/GT/86-02

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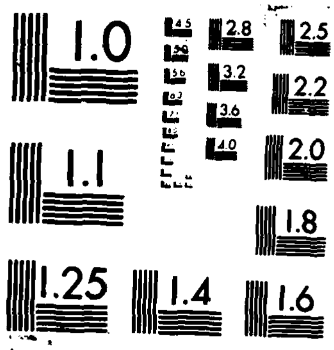

CROCOPY RESOLUTION TEST CHART

5.0 SUMMARY AND CONCLUSIONS

5.1 Research Summary and Conclusions:

The objectives of this research program were to (a) develop techniques to isolate and characterize the effects of membrane compliance during undrained triaxial testing of saturated soils, (b) develop and implement a technique to eliminate the adverse effects of membrane compliance during undrained testing, and (c) experimentally demonstrate the effectiveness of the membrane compliance mitigation methodology developed. Although all testing was performed using "small-scale" triaxial testing apparatus (capable of testing samples up to 2.8 inches in diameter), an overriding consideration was the requirement that the membrane compliance mitigation methods developed be suitable for adaptation to large-scale undrained triaxial testing of coarse, gravelly soils. In addition, it was considered highly desirable that the mitigation methods for "small-scale" (conventional) testing utilize equipment and procedures suitable for widespread adoption at reasonable cost and without requiring extensive modifications of existing testing apparatus.

The membrane compliance mitigation procedures developed consisted of first pre-determining the volumetric magnitude of membrane compliance for a given soil of given density as a function of effective confining stress, and then using a computer-controlled process to continuously inject or remove water from the sample during testing in order to exactly offset the volumetric error induced by membrane compliance. The computer-controlled injection removal system developed used an IBM PC-AT microcomputer with a Metrabyte A/D and D/A conversion board, and a GDS digital pressure controller whose internal electronics were bypassed to allow the microcomputer to directly control the digital-motor-driven injection piston. The total hardware cost of this system was less than $11,000, and significant savings can be made by adopting less

expensive microcomputers if desired. No modifications of existing triaxial testing apparatus were required for implementation of the injection-mitigation system: the system required a single connection to the sample drain lines and operated completely independently of other test control and data acquisition systems.

In order to implement this technique, it was first necessary to demonstrate that volumetric compliance could be reliably measured prior to testing, and that it could be reliably characterized in such a manner that the computer-controlled injection/removal process could be based on monitoring of changes in sample effective confining stress and geometry. A "two-sample, scale model" method for evaluation of volumetric membrane compliance was proposed in Section 2.1.2. Chapter 3 summarized the results of a study of volumetric membrane compliance using this technique. It was demonstrated that the volumetric error induced as a result of membrane compliance was a direct and repeatable function of changes in effective sample confining stress, and that monitoring these changes in effective stress provided a suitable basis for continuous computer-controlled injection/correction during "undrained" testing.

Undrained monotonic and cyclic triaxial loading tests were performed on samples of a uniformly graded medium sand, with and without implementation of the computer-controlled membrane compliance mitigation methodology developed, in order to provide a basis for evaluating the effectiveness of the compliance mitigation procedures. The results of these tests provide good support for the effectiveness of the membrane compliance mitigation procedures proposed and implemented in these studies.

The monotonic testing program demonstrated that the residual or critical state conditions in tests without implementation of membrane compliance

mitigation methods are potentially misleading if interpreted as representing "undrained" test results. If these conventional tests (without mitigation) are interpreted correctly as "partially drained" tests (correctly accounting for membrane compliance-induced volume changes), they agree closely with the results of tests performed implementing the compliance mitigation methods developed. Membrane compliance was shown to have a significant influence on the undrained monotonic triaxial load response of saturated medium sand samples 2.8 inches in diameter.

The cyclic triaxial testing program also showed that membrane compliance effects were significant when testing 2.8-inch diameter samples of medium sand at a relative density of approximately 50%. A cyclic strength curve developed by testing such samples "conventionally" (without mitigation of compliance effects) was shown to represent a higher resistance to liquefaction than the strength curve based on tests performed with mitigation of compliance effects. The apparent overestimation of liquefaction resistance due to membrane compliance was approximately 20% in terms of cyclic stress ratio for failure at any given number of cycles. The cyclic strength curve based on tests performed with continuous mitigation of membrane compliance effects was shown to agree well with the cyclic strength curve for a mineralogically similar but finer sand, of parallel gradation and from the same borrow source, at similar relative density. Tests of this finer sand would not be expected to be significantly affected by membrane compliance.

In summary, methods have been developed for characterization and mitigation of membrane compliance effects in undrained triaxial testing of saturated soils. These methods have been implemented for both monotonic and cyclic testing of samples 2.8 inches in diameter, and the results of the testing program provide good support for the accuracy and effectiveness of the methods developed.

5.2 Suggestions for Further Research:

Now that an apparently successful procedure for mitigation of membrane compliance effects has been developed and implemented for small-scale triaxial testing, a number of additional research opportunities exist. The following is a brief description of several of these areas warranting further investigation:

1) Large-Scale Triaxial Testing for Verification of Membrane Compliance Mitigation Techniques: The small-scale monotonic and cyclic triaxial testing programs performed as part of these studies provide strong, but not conclusive, support for the accuracy and effectiveness of the compliance mitigation techniques developed. A more conclusive investigation of their effectiveness could be performed by duplicating some of these small-scale tests on large-scale (> 12-inch dimaeter) samples, as such large-scale samples of Monterey 60 sand would not be significantly influenced by membrane compliance effects.

2) Small-Scale Testing and Development of Theoretical or Empirical Procedures for Post-Testing Correction for Membrane Compliance Effects: Small-scale monotonic and cyclic tests performed with and without implementation of the injection-mitigation techniques provide a means to develop the data base necessary for development and verification of theoretical and/or empirical models for (a) prediction of the influence of membrane penetration on undrained tests and (b) post-testing correction of "conventional" undrained test results.

3) Implementation of Membrane Compliance Mitigation Procedures for Large-Scale Testing of Gravelly Soils: The injection-mitigation methods developed are designed to be suitable for adaptation to large-scale triaxial

testing. This could be accomplished either by upscaling the injection pistons (and/or using several pistons in parallel), or by establishing a simple manually controlled system for injection/removal. The relatively large volumes of water to be injected/removed in large-scale testing of gravelly soils may be manually controlled with adequate accuracy if testing proceeds slowly. A computer-controlled system offers obvious advatanges in terms of speed, accuracy, and elimination of likely operator error in a manually controlled system. There is, at present, no accurate and reliable methodology for performing representative undrained tests on coarse gravelly soils, and development of large-scale triaxial testing facilities successfully implementing procedures for mitigation of membrane compliance effects would allow, for the first time, extensive investigation of the true load response characteristics of coarse gravelly soils under undrained conditions.

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